DESIGN, CONSTRUCTION, AND EVALUATION
OF A PROTOTYPE LOW-ENERGY
LAKE DESTRATIFIER

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CHAPTER I

INTRODUCTION

The Problem

The impoundment of water is an important source of water for agriculture, recreation, municipalities and industries. Although generally these reservoirs offer a source of good quality water, at times their water quality deteriorates. This deterioration is caused by natural forces, but is greatly accelerated by man's activities. If this deterioration could be avoided or reduced by some method of in-reservoir treatment the additional burden placed on water treatment plants could be reduced. The aesthetic and chemical problems could be improved, allowing full utilization of the impoundment by man and wildlife.

The natural force having the greatest effect on water quality deterioration is the seasonal heating and cooling process of a body of water. At the end of a winter season, water in a reservoir is usually of fairly uniform quality and has a relatively low temperature. As atmospheric temperature increases in the spring, surface waters begin to warm, and a strata of less dense water is formed over the colder bottom waters. This surface strata, termed the epilimnion, is kept in circulation by the wind, and remains rich in oxygen and fairly uniform in temperature. Because the average daily wind does not produce enough force to set the whole body of water in motion, a second strata is formed. This strata, termed the thermocline, is a transition zone of rapidly decreasing temperature and oxygen. This zone acts as a diaphragm preventing surface-induced circulation below its depth, thus forming a third strata. This bottom strata, termed the hypolimnion, is at a fairly uniform lower temperature and frequently becomes depleted of oxygen by chemical reduction processes and biological respiration. When a body of water transforms into these three strata, it is said to be stratified.

As dissolved oxygen (DO) becomes depleted, anaerobic conditions prevail and many deteriorating chemical reactions can occur leaving the hypolimnion waters high in hydrogen sulfide, ammonia, iron, manganese, phosphates, nitrates, and other toxic substances (1).

In the fall as atmospheric temperature decreases, the surface waters cool until an unstable condition exists (denser water at the surface), and a natural lake turnover occurs. This turnover releases the anoxic waters of the hypolimnion into the whole body of water and if accompanied with low oxygen concentrations in the epilimnion, can result in massive fish kills. The fall turnover also places an excessive burden on water treatment plants.

The common practice of releasing impounded waters to improve water quality in streams during low flows is also affected by stratification. Many of our present reservoirs have the inlet structure located in the hypolimnion and when hypolimnion water is released into streams, water quality could be lowered instead of improved. This lower quality water can also cause downstream fish kills (1).

The adverse effects of stratification have prompted researchers to develop means of controlling this problem. Three major systems for controlling stratification have been developed: (1) diffused-air pumping, which is the process of releasing compressed air near the bottom and letting it rise to produce a mixing action; (2) mechanically pumping the lower waters to the surface, and (3) aerating the hypolimnion waters without destroying the thermal stratification. These systems have been successful in improving water quality by destratifying lakes and reservoirs. Unfortunately, many of these devices are high energy consumers, require costly complicated equipment, and have high maintenance requirements.

Quintero and Garton (2, 3) developed a low-energy lake destratifier. It was an axial flow pump that moved the warm, oxygen-rich waters of the epilimnion to the colder, oxygen depleted waters of the hypolimnion. The pump was very simple. It consisted of a propeller and stationary casing mounted underneath a floating structure. The propeller was powered by an electric motor. Their study involved only the mechanical aspects of the pump's operation.

Steichen and Garton (4, 5) used a modified version of the Quintero and Garton destratification device to determine the effectiveness of the pump's operation on lake destratification. The effectiveness was determined by observing various physical-chemical and biological parameters.

Continued study of the axial flow pump as a destratification device is reported in this research.

Objectives

1. To design and construct a prototype, low energy, axial downflow pump for use as a destratification device.
2. To evaluate the performance and design of the pump

when moving water under a low head.

3. To determine the effect of the pump's operation on the water quality parameters of a stratified lake.

Limitations of the Study

Since a prime objective of this project was the design of a low-energy lake destratifier, a maximum power requirement of 746 watts was selected.

The maximum flow rate was limited by the 746 watt electric motor, the 100:1 gear reduction and the 1.83 meter propeller.

Velocity profile measurements of the pump were limited to the 4.42 meter radius of the traverse device.

A limit on the number of physical and chemical parameters measured was made because of the time involved. Temperature, DO, alkalinity, pH, conductivity, solids, iron, turbidity, manganese, clarity, and chemical oxygen demand (COD) were measured. The only measurement involving biological factors was the five-day biochemical oxygen demand (BOD_5).

CHAPTER II

REVIEW OF LITERATURE

The practice of impounding small streams as a method of water storage for domestic and industrial use has become a common practice in water resource management. Reservoirs and lakes, however, are subject to a wide combination of physical, chemical, meteorological, and biological phenomena. The detrimental effects of these phenomena must be controlled before the practice of impoundment can be fully utilized.

Effects of Impoundment

The influence impoundment has on water quality has attracted many researchers (6, 7, 8, 9, 10, 11). Love (6) states some of the more significant beneficial effects include: (1) reduction of turbidity, silica, color (in certain reservoirs), and coliform bacteria, (2) evening out of sharp variations in dissolved minerals, hardness, pH, and alkalinity, (3) reduction in temperature, which sometimes benefit fish life, (4) entrapment of sediment, and (5) storage of water for release in dry periods for the dilution of polluted waters. The more significant detrimental effects include: (1) increased growth in algae, which may give rise to taste and odors, (2) reduction in DO in the deeper parts of the reservoir, (3) increase in carbon dioxide (CO_2) and frequently iron, manganese, and alkalinity, especially near the bottom, (4) increases in dissolved solids and hardness as a result of evaporation and dissolution of rock materials, and (5) reductions in temperature, which, although sometimes beneficial, may be detrimental to fish life.

It was concluded by Silvey (7) that water quality in reservoirs normally will become lower as the reservoir ages. Accumulation of the remains of microorganisms, mineralization due to high evaporation, slow accumulation of pollution materials, continuous reduction in water flow for the total number of reservoirs, increased use by municipalities and industrial organizations, and irrigation will result in rapid depletion of high quality water.

Thermal Stratification

Hutchinson, in A Treatise on Limnology (12), describes the process by which a lake that is cooled in the spring is transformed into a thermally stratified lake in the summer.

> The heating of a lake in the temperature latitudes begins when the entire body of water is near 4 °C, the temperature of maximum density. If such water were of uniform transparency and were quite undisturbed, radiation entering the water surface and being absorbed exponentially would heat the water at a rate falling exponentially from the surface, and so would produce an exponential temperature curve. Two principal factors prevent such a process from taking place or ever being approached. First, evaporation will always cool the surface layer, setting up convection currents. These currents will be enhanced by back-radiation and loss of sensible heat, especially at night. Second, the lake surface will never be undisturbed by the wind setting up currents and turbulent motion leading to mixing and downward transport of momentum and heat.
>
> The form of the resulting temperature distribution is exceedingly characteristic. In all lakes of sufficient depth, heating in the spring from a low temperature, the water tends to become divided into an upper region of more or less uniformly warm, circulating and fairly turbulent water termed the epilmnion, and a deep, cold and relatively undisturbed region termed the hypolimnion (12).

A boundary is thus formed between the turbulent surface stratum and the quiet water masses underlying it. This boundary has been termed the thermocline, and more recently the metalimnion. Figure 1 illustrates the division of the three layers in a stratified lake.

In a stratified impoundment, the thermocline is defined as the zone of water in which the temperature gradient is equal to or greater than a decline of 1 °C per meter of depth. Such a definition is quite arbitrary since in a warm lake a thermocline of less than 1 °C per meter could be stable. Hutchinson (12) suggests defining the thermocline as the plane of maximum rate of decrease in temperature, or in more formal terms the plane defined by:

$$\theta'' = \frac{d^2\theta}{dz^2} = 0 \qquad (2\text{-}1)$$

Symons, et al. (8), states that because the decrease in density for each degree centigrade is much greater at warmer temperatures than at colder ones, the density profile, not the temperature profile, determines the thickness of the stratum of water that must be mechanically mixed if artificial circulation is to be accomplished.

The expenditure of energy necessary to upset an existing stratification or to bring it to a state where the whole mass would have taken on the mean temperature of mixing is important to anyone attempting to destratify a body of water. This expenditure of energy has been defined as the stability of stratification.

Since the center of gravity of a stratified body of water lies lower than that of an unstratified one (because denser layers are below), Ruttner (13) defines stability as the work required to raise

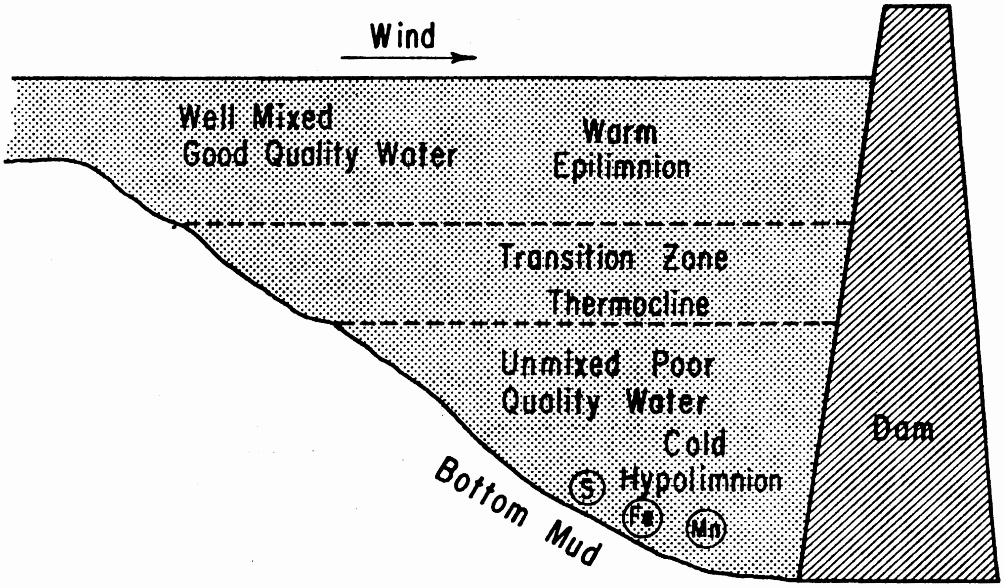


Figure 1. Typical Summer Thermal Stratification Pattern
After Symons, J. M. (11)

the center of gravity an amount corresponding to its displacement downwards from its original position. This is equivalent to lifting the weight of the whole lake by a distance equal to the difference between the two centers of gravity.

Symons, et al. (14), suggests destratification efficiency as a useful way of comparing the mechanical performance of artificial destratification devices. The destratification efficiency (DE) for any lake mixing operation is defined by the ratio:

$$\text{DE} = \frac{\text{Net change of stability from } t_1 \text{ to } t_2}{\text{Total energy input from } t_1 \text{ to } t_2} \text{ X } 100 \qquad (2\text{-}2)$$

in which t_1 is the time of start of mixing and t_2 is the time of end of mixing.

Symons further states that to evaluate the ability of any destratification device to add DO and oxidize oxygen sinks, the oxygenation capacity (OC) is used and has been defined by the ratio:

$$\text{DE} = \frac{\text{Net change of stability from } t_1 \text{ to } t_2}{\text{Total energy input from } t_1 \text{ to } t_2} \text{ X } 100 \qquad (2\text{-}3)$$

Eutrophication

Lake eutrophication is a term that has been defined, redefined, and used in many different contexts by many authors to explain the enrichment of waters. Greeson (15) classifies eutrophication as a natural aging process that affects every body of water from the day of its formation. This natural aging process can be accelerated by man's activities, which introduce excess nutrients along with other pollutants into bodies of water, thereby causing significant changes in the aquatic environment.

Most researchers use the term eutrophic to mean highly nourished, mesotrophic to mean an average degree of nourishment, and oligotrophic to mean poorly nourished. Figure 2 illustrates some of the differences between the oligotrophic lake (A) and the eutrophic lake (B). The curves give the typical late-summer temperature and oxygen concentrations (O_2).

A sign of eutrophic conditions is the presence of prolific quantities of aquatic weeds along the shoreline. In deep lakes which become thermally stratified, the lack of oxygen in the bottom waters is also a symptom of eutrophic conditions (16). It must be noted, however, that oxygen deficits are not necessarily indicative of eutrophic conditions.

As a lake or reservoir becomes rich in nutrients it develops dense populations of planktonic algae that are usually dominated by a few species of the blue-green variety (17). These dense populations create taste and odor problems, along with an increase in organic loading of the lower layers as the algae complete their life cycle and fall to the bottom.

King (18) states that although nitrogen, phosphorus, and a variety of other nutrients are required by algae, eutrophication seems to be ultimately a carbon-accumulation phenomenon. The amount of nitrogen, phosphorus, and other plant nutrients required to produce midsummer blue-green algal dominance in any lake seems to be related directly to the bicarbonate-carbonate alkalinity of that lake.

Aside from the esthetic deterioration of water quality,

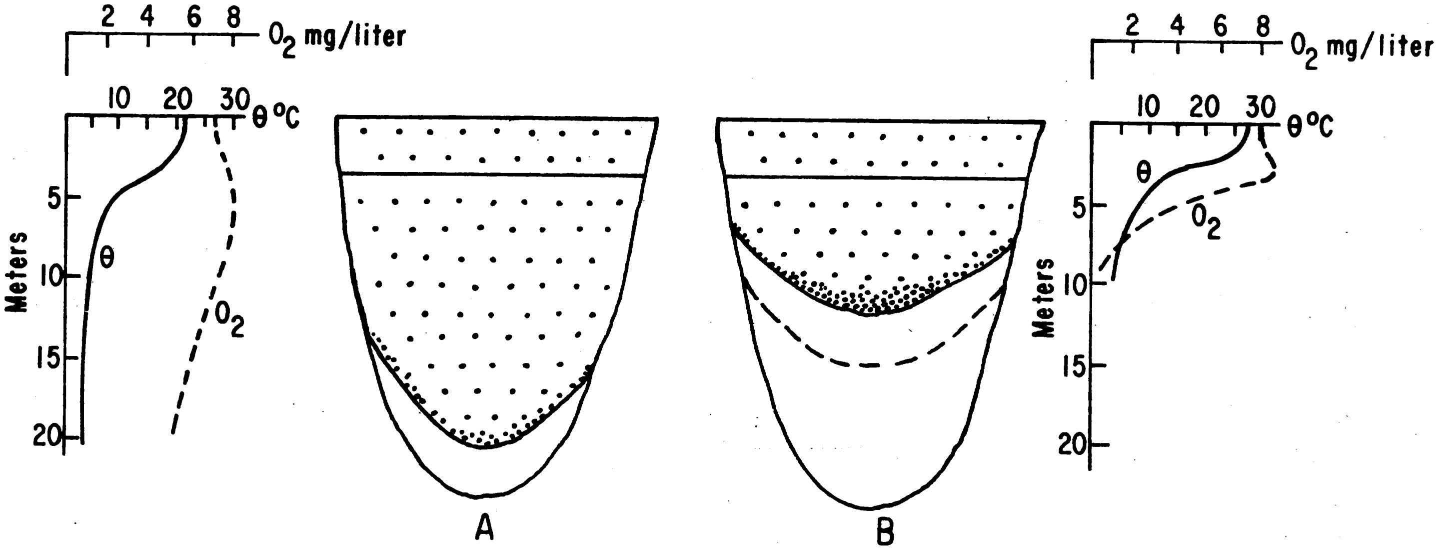


Figure 2. Diagrammatic Representation of an Oligotrophic Lake, A, and a Eutrophic Lake, B. After Hutchinson, G. E. (12)

eutrophication presents many other difficulties for water plant operators. Warm water is less palatable than cold water; algae-laden water has high chlorine and coagulant demands. It often reduces filter runs, necessitating excessive backwash; it may also require certain specific forms of taste and odor control such as activated carbon, chlorine, dioxide, or permanganate (19).

Effects of Destratification

Stratification has previously been defined as the development of three distinct layers in a lake or reservoir, the epilimnion, thermocline, and hypolimnion. Therefore, the primary effect of destratification is to break these layers and allow the entire water mass to mix. The whole body of water would then become isothermal, and other chemical parameters would be brought to some mean value.

When a lake or reservoir becomes stratified, the natural oxygen demand of the dense water in the hypolimnion removes the DO from solution. When the DO concentration goes to zero, several reactions take place. Under this anaerobic condition, iron and manganese are reduced and go into solution; sulfates are reduced and odorous hydrogen sulfide is formed; excess CO_2 is created and the pH of water is lowered and aerobic biodegradiation of organic materials ceases (11).

In the fall, the surface waters cool faster than the lower waters of the reservoir until an unstable condition develops (the denser water at the surface) causing a natural turnover of the water mass. The anaerobic products of the hypolimnion are then spread throughout the entire body of water, and taste and odor problems occur regardless of the depth from which water is taken. Fish life may be curtailed or eliminated completely due to the absence of DO and the release of toxic anaerobic products.

Artificial destratification in general would not produce such an instantaneous turnover. If artificial destratification were started in early spring the anaerobic conditions of the hypolimnion would never develop.

Most researchers (20, 21, 22, 23, 24, 25, 26) who artificially destratified a lake or reservoir showed pronounced increases of DO in the hypolimnion and sometimes slight decreases in the epilimnion. This decrease in the epilimnion is thought to be due to the increased organic load brought up from the hypolimnion by mixing.

Riddick (20) concluded from his study some of the effects of artificial destratification: (1) iron and manganese in the thermocline and hypolimnion were oxidized and precipitated out; (2) color was reduced, (3) CO_2 was reduced to normal (atmospheric) saturation values (one to three mg/l) throughout the entire depth of the reservoir, (4) bicarbonate alkalinity was readily increased, (5) pH values leveled off in the range of 6.8 to 7.3, and (6) elimination of most algae blooms. Other researchers (11, 22, 23, 27, 28) showed similar effects.

Other advantages attributed to destratification has been a definite reduction in chlorine demand during the summer months which has resulted in savings in chlorine cost and stocking of the reservoir with trout without adverse effects during the summer season (29).

Teerink and Martin (30) reports benefits to fisheries that accrue from destratification include: (1) increased living space for fish; (2) increased living space for fishfood organisms, and (3) dispersion of fish toxicants and reduction of detoxification time. The only deleterious effect reported to be expected from artificial destratification was that caused by an increased in the heat budget of the reservoir.

The Quality Control in Reservoirs Committee of the American Water Works Association (31) recommends artificial destratification as a relatively inexpensive technique to water suppliers who are experiencing raw-water quality deterioration in their reservoirs as a result of stratification.

Methods of Artificial Destratification

There are two basic systems that have been used to thermally destratify a body of water. They are mechanical and diffused-air pumping.

Diffused-Air Pumping

The basic system of diffused-air pumping consists of releasing compressed air near the bottom of the lake or reservoir. The rising air bubbles set the entire mass of water in motion and can completely mix the body of water. Some of the oxygen in the air bubbles is diffused into the water, but the major effect is the mixing action caused by the rising air bubbles. Diffused-air pumping is also characterized by having high power requirements, high friction losses in the distribution lines, and the inherent low efficiencies of air lift pumps.

Falmouth Lake in Kentucky was destratified with compressed air released through 16 porous ceramic diffusers placed in a cross pattern on the lake bottom. The diffused-air pump system was a 22.4 kilowatt (kW) portable, electrically driven, rotary air compressor. The lake had a surface area of about 91 hectares, a capacity of about 567 hectare-meters, and a maximum depth of 13 meters. Destratification efficiencies ranged from 0.2 to 0.9 percent (14). In this same study, Boltz Lake was destratified using the same system used on Falmouth Lake. This lake had a surface area of about 40 hectares, a capacity of about 361 hectare-meters, and a maximum depth of 19 meters. Destratification efficiencies ranged from 0.6 to 1.5 percent.

The aerohydraulic gun, or bubble gun, has been used to destratify a body of water. The gun consists of a vertical tube and a chamber at the bottom, working on the principal of a siphon, which intermittently releases large air bubbles. The bubbles fit snugly in the tube and rise, acting as a piston, to force out water above the bubble and draw in water through ports in the tube located just above the air distributor (26).

Indian Brook Reservoir was destratified with compressed air released 2.3 meters below the surface. The power requirement was about 6 kW. The reservoir had a surface area of about 8.5 hectares, a capacity of about 39 hectare-meters, and a maximum depth of 8.5 meters. Complete thermal destratification was achieved in four to six days (20).

Mechanical Pumping

Destratification of a lake or reservoir can be achieved by mechanically pumping the dense water of the hypolimnion to the surface where it is discharged into the epilimnion, or by pumping the warm, oxygen saturated water of the epilimnion to the hypolimnion.

Irwin, et al. (28), destratified several lakes in eastern Ohio by pumping the hypolimnion waters to the surface. The mechanical pump was a 30.5 centimeter diameter mixed-flow pump, with a power requirement of approximately 9 kW. The pump had a capacity of 1.6 hectare-meters per day. The smallest lake, Stewart Hollow, had a surface area of 3.2 hectares, a capacity of about 14.8 hectare-meters, and a maximum depth of 7.6 meters. The largest lake, Vesuvius, had a surface area of 42.5 hectares, a capacity of about 155 hectare-meters, and a maximum depth of 9.2 meters. Successful destratification was reported in all lakes studied.

Steichen (4) used a modified version of the pump reported by Quintero (2) to destratify Ham's Lake in Oklahoma. The axial flow pump was used to pump the epilimnion waters down into the hypolimnion. The pump was capable of pumping 6.4 hectare-meters per day (0.74 m^3/sec) using 0.373 kW. The lake had a surface area of 40 hectares, a capacity of about 115 hectare-meters, and a maximum depth of 9.5 meters. Destratification efficiencies ranged from 4.6 to 6.0 percent.

Hypolimnion Aeration

Hypolimnion aeration is basically the aeration of the hypolimnion waters without destroying the thermal stratification of the impoundment. The major advantages include: (1) the temperature of the water is not increased, (2) nutrients in the hypolimnion capable of supporting algal growth are not made available, thus restricting algal productivity, and (3) less volume of water is involved since the epilimnion is not involved.

The hypolimnion waters of Wahnbach Reservoir were aerated with a system developed by Bernhardt (32). This system consisted of a vertical pipe extending from just above the bottom to three meters above the surface. The vertical pipe had four distribution pipes at the top of the hypolimnion. Compressed air was released, at the bottom of the vertical pipe, through a diffuser causing the water in the pipe to rise and flow out the distribution pipes.

Speece (33) describes several other methods for hypolimnion aeration without destroying thermal stratification.

A modification of U-tube aeration has been used for hypolimnion aeration. This system consists of pumping the hypolimnion waters to the surface, injecting air, and pumping back into the hypolimnion.

Hypolimnion aeration using deep oxygen-bubble injection is based on the concept of injecting an oxygen bubble deep enough in the impoundment so that essentially the oxygen is completely absorbed before the bubble rises out of the hypolimnion.

A down flow bubble contact aerator, capable of efficiently absorbing commercial oxygen, consists of an open-bottom pyramidal or conical hood with a motor-driven propeller mounted in an opening at the top to draw in large volumes of water. Commercial oxygen is injected through a dispenser located below the propeller. The hood is designed so that the water velocity leaving the bottom of the hood is less than the buoyant velocity of the bubbles to prevent sweeping them out of the system.

Design of an Axial Pump

An axial flow or propeller pump, the type used in this study, is a pump in which most of the head produced by the propeller is due to the pushing or lifting section of the vanes. The fluid enters and leaves the impeller in an axial direction. It operates just like a venting fan enclosed in an orifice, except that it moves liquid instead of air (Figure 3).

Previous Work

Quintero (2) was the first to study the use of a high volume, low head propeller pump for destratifying a body of water. Quintero used a seven-bladed propeller which had an effective diameter of 1.06 meters, and was originally designed for blowing air. The angle of the blades was 20° at the base and 10° at the tip. The conclusions reached from this study include: (1) the pump was able to pump large volumes of water with a low input of energy, (2) the rotative velocity of the propeller shaft was the significant factor affecting both the flow and the power input of the pump, (3) the efficiencies of the pump were low, (4) calculated values of specific speed varied from 72,000 to 125,000 as compared to values of 7,500 to 14,000 for typical axial flow pumps, and (5) the pump should be a practical means of pumping water from the top of a reservoir to the bottom with a low input of energy.

Steichen (4) used a modified version of Quintero's pump to destratify Ham's Lake in Oklahoma. The modifications included changing the propeller and designing a rigid diffuser. A nine-bladed propeller with an effective diameter of 1.06 meters was used. The chord angle of the blade varied from about 44° near the hub to about 20° at the tip. This propeller was originally designed for blowing

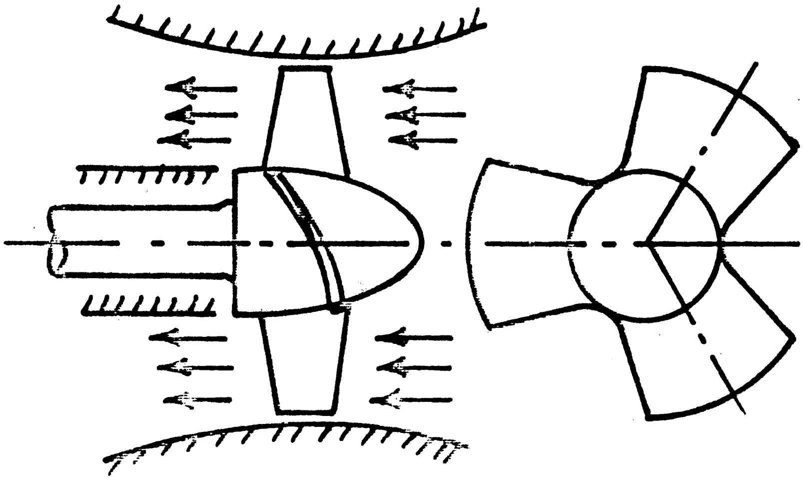


Figure 3. Axial Flow or Propeller Type Pump

air. The conclusions obtained from this study include: (1) within two weeks the pump completely destratified the lake thermally, (2) a longer period of time was necessary to destratify the DO, (3) the pump was capable of destratifying the lake without the diffuser attached, (4) destratification of all physical-chemical parameters was observed, (5) no significant improvement in diffuser efficiency was found in comparing the rigid metal diffuser with a flexible fabric diffuser, and (6) use of the propeller with a pitch varying from 44° at the hub to 20° at the tip resulted in as much as 49 percent more flow at the same power as a propeller with pitch from 20° to 10°.

Garton and Rice (34) attempted to destratify Lake Arbuckle in south central Oklahoma. The lake has a surface area of approximately 975 hectares, a volume of approximately 8,600 hectare-meters, and a maximum depth of about 27.5 meters. The destratifier unit consisted of a 5.03 meter aircraft propeller, powered by an industrial gasoline engine and located near the deepest part of the reservoir.

In 1975 the pump was operated from June 2 to July 2 at 18 RPM, with a 6.5° tip angle. The pump produced a flow lf 11.7 m^3/sec with 5.33 kW of power. It was then operated from July 2 to September 13 at 20 RPM, and produced a flow of 13.1 m^3/sec with 7.32 kW of power. The natural fall turnover occurred on September 13.

Although the lake was not completely destratified, several facts were learned from this study. Prior to the natural fall turnover the lake stability index had been decreased by half, but a corresponding reduction in oxygen stratification did not occur. This suggests a lake can be weakly stratified thermally and strongly stratified chemically. For this reason, the authors propose the use of an oxygen distribution index to serve the same function for oxygen that the stability index serves for temperature. It is calculated in the same way except that the weight of oxygen in the slice is used instead of the weight of water. The index gives a single number which is a measure of the oxygen distribution of the lake. A value of zero indicates that the lake is completely destratified for oxygen.

The study also showed that the fall turnover occurred about a month earlier than usual. After the turnover the lake was more completely mixed than in previous years. Also, the oxygen content in the outlet water released near the destratifier was maintained at a level about one to two milligrams per liter (mg/l) higher than the level in the main body of the lake.

Performance

The performance of an axial pump is generally described in terms of the following characteristics: (1) rate of flow, or capacity Q, expressed in units of volume per unit of time, (2) increase of energy content in the fluid pumped, or head H, expressed in units of energy per unit of mass, (3) input power P, expressed in units of work per unit of time, (4) efficiency η, the ratio of useful work performed to power input, and (5) rotative speed N, in revolutions per minute (RPM) (35).

Fan Laws

At constant orifice ratio or at constant specific speed for fans of geometrically similar design the following relations are valid:

$$Q \propto D^3N$$

$$H \propto D^2N^2\rho$$

$$P \propto D^5N^3\rho$$

From these relationships we can state:

$$\frac{P}{Q} \propto \frac{D^5N^3\rho}{D^3N} \propto H \propto \frac{V^2}{2g}$$

From this relationship it can be seen that to minimize the power requirement per unit of flow a large diameter, low RPM propeller is required.

For any given fan, diameter (D) is constant and at constant orifice ratio the fan laws are: (1) volume varies directly with the speed, (2) head varies with the square of the speed and directly as the density, and (3) power varies as the cube of the speed and directly as the density (35).

Therefore, with diameter constant, the following relations are valid:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{2-4}$$

$$\frac{H_1}{H_2} = \frac{\rho_1 N_1^2}{\rho_2 N_2^2} \tag{2-5}$$

$$\frac{P_1}{P_2} = \frac{N_1^3 \rho_1}{N_2^3 \rho_2} \tag{2-6}$$

CHAPTER III

EXPERIMENTAL DESIGN AND EQUIPMENT

Destratifier Unit

The destratifier unit consisted of an electric motor, a gear-reduction drive, a floating platform, a propeller and an orifice shroud (Figures 4 and 5).

Pump

Keeping in mind the initial limitation, a maximum power requirement of 746 watts, a DCH72 Acme Windmaster fan and orifice shroud was purchased.

The six-bladed propeller (Figures 6 and 7) had an effective diameter of 1.77 meters. The blades had an effective width of 0.305 meters and the chord angle varied from about 60° at the hub to about 25° at the tip. The hub was 0.46 meters in diameter and was 0.25 meters tall. The blades were reinforced at the hub. The propeller was held in place by two sleeve and thrust bearings.

The shroud was two meters square and had an orifice diameter of 1.85 meters (Figure 8). The orifice rim or lip was 7.0 centimeters wide. The shroud and propeller were rust protected with five coats of baked epoxy paint. The pump was covered with galvanized, welded wire fence to prevent fish and debris from entering the propeller.

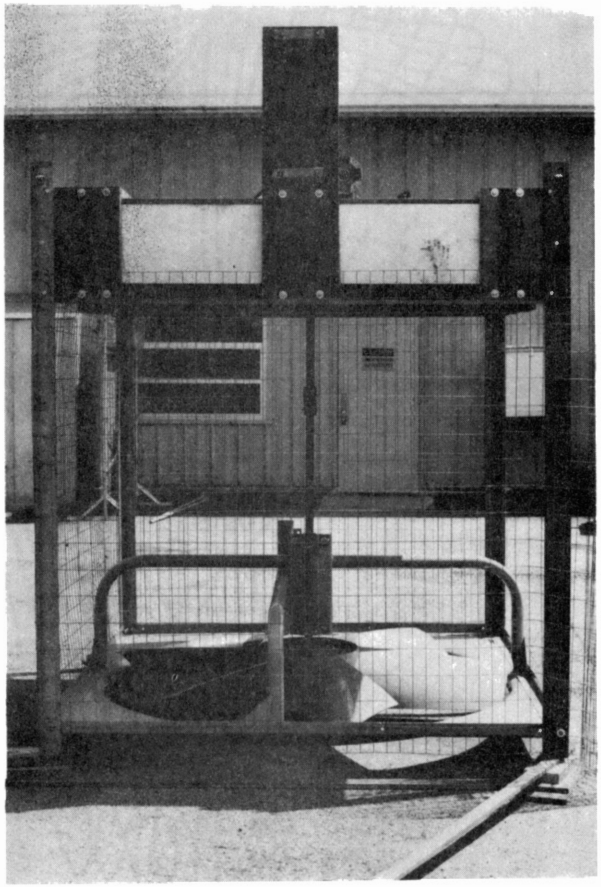


Figure 4. Side View of Destratifier Unit

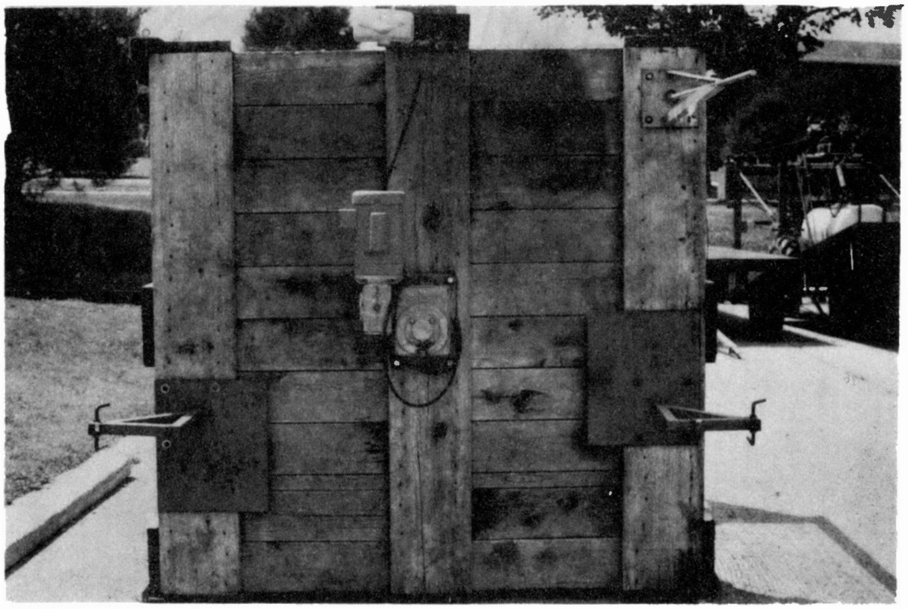


Figure 5. Top View of Destratifier Unit

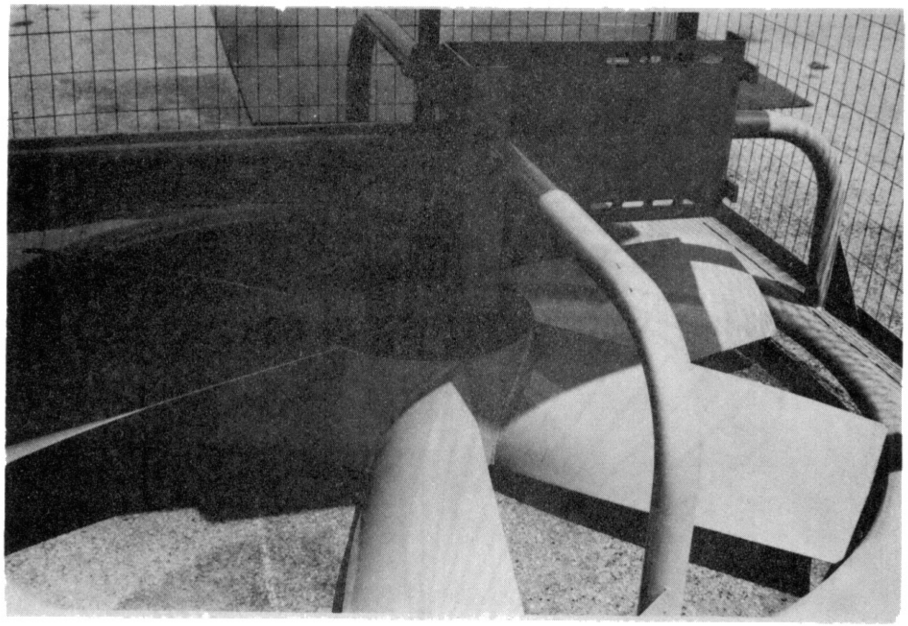


Figure 6. General View of Propeller

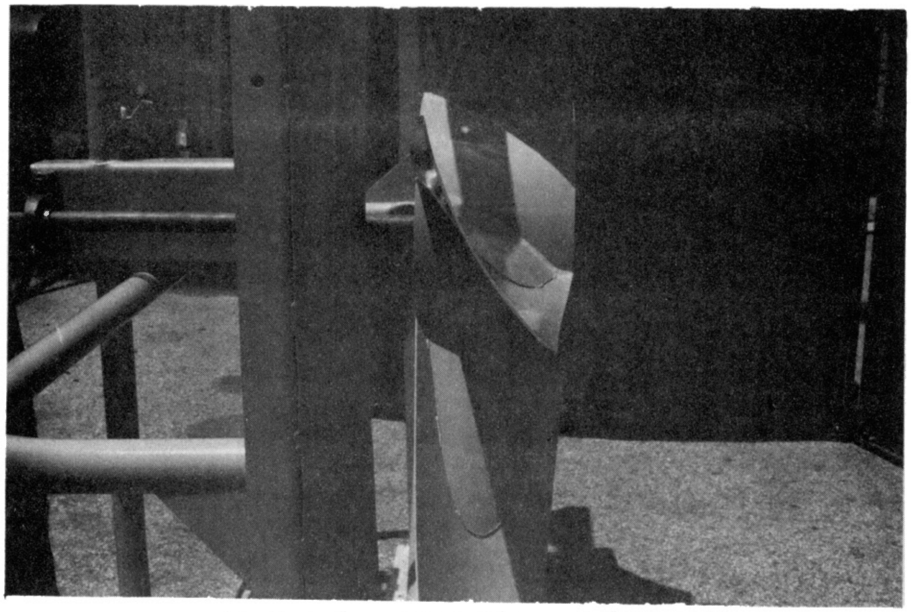


Figure 7. Side View of Propeller

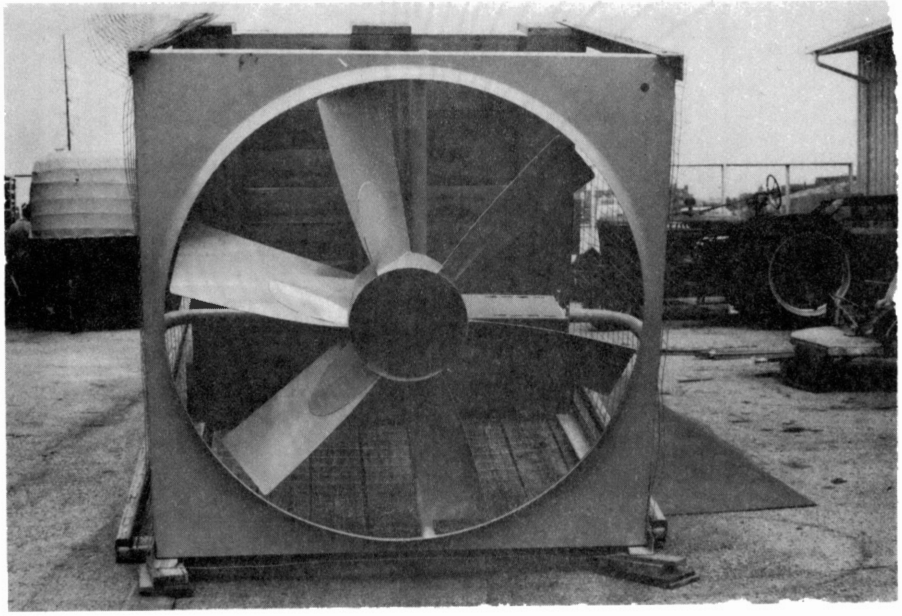


Figure 8. Pump Orifice Shroud

The propeller and shroud had originally been designed for moving air and was capable of pumping 21.3 m^3/sec with a power requirement of 1716 watts, at 226 RPM.

Performance of the propeller in water was obtained by use of Equations (2-4) and (2-6) and the manufacturer's stated performance in air. Calculations showed, at the maximum power requirement of 746 watts, the pump would produce a flow of 1.72 m^3/sec at 18.2 RPM. Knowing these conditions, a 1750 RPM Baldor electric motor and a 100:1 Morse right angle gear-reduction was purchased. Calculations showed at 17.5 RPM, the pump would produce a flow of 1.65 m^3/sec and require 663 watts of power.

Supporting Platform

A redwood, expanded foam, sandwich raft (Figure 9), two meters square, supported and located the pump on the lake. The raft had a flotation capacity of about 1730 kilograms and was held in place by anchors connected to each corner. Connection of the raft to the pump was simplified by making the raft equal in size to the shroud. Aluminum angles 8.2 centimeters by 10.2 centimeters connected the corners of the raft to the corners of the shroud. Location of the propeller was 1.8 meters below the water surface.

Power Source

A 120/240-volt single-phase electrical power supply was brought from shore by an underwater cable. A 746-watt Baldor totally enclosed electric motor was directly mounted to a 100:1 Morse right angle gear-reduction (Figure 10). The gear drive was connected to the

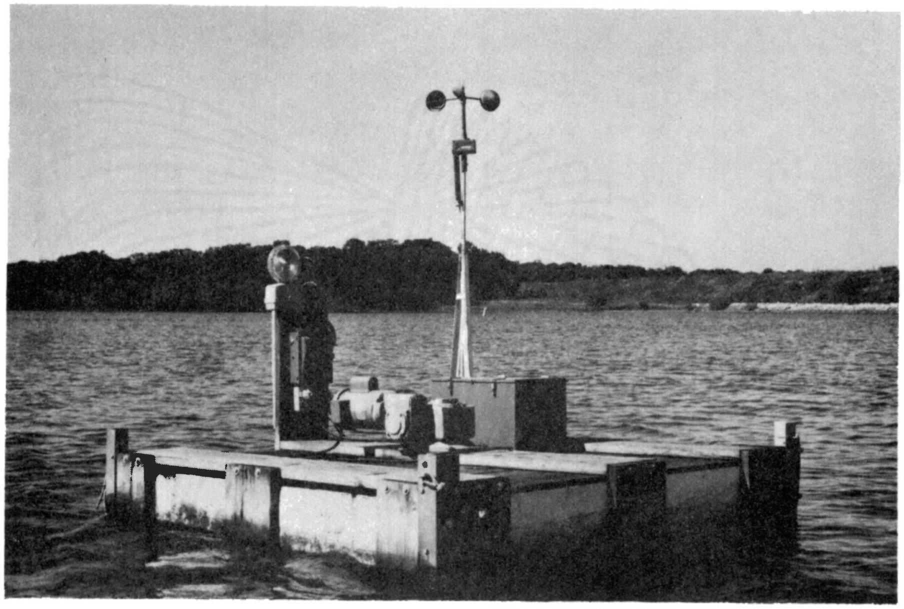


Figure 9. General View of Pump

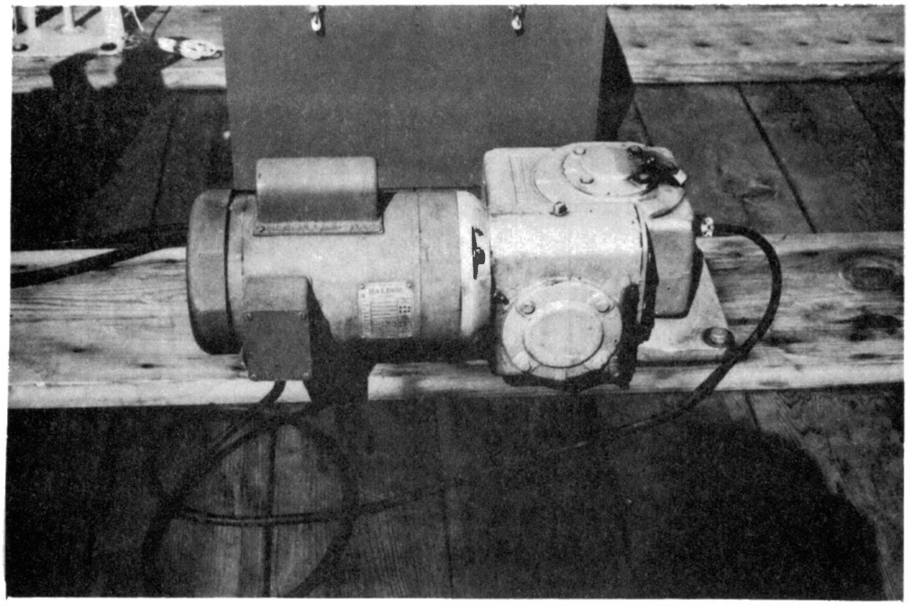


Figure 10. Motor and Gear Reduction

propeller with a 3.65 centimeter diameter steel shaft. This system limited the operation to one propeller speed.

Measuring Devices

Velocity of the water discharged by the pump was measured using a laboratory "Ott" current meter. This factory calibrated propeller meter, 50 millimeters in diameter with a 0.05 pitch, was capable of measuring velocities in the range of 0.05 to 3.0 m/sec. The propeller was mounted in a 9.84 centimeter inside diameter by 31.75 centimeter conduit to allow only the vertical component of the water velocity to be measured (Figure 11). The propeller calibration equation was used to calculate the water velocity based on the RPM of the propeller. Profile measurements were determined using the traversing mechanism shown in Figure 12.

Power input to the electric motor was measured using a General Electric Type AP-9 wattmeter. A calibration curve was determined using a prony brake to measure the propeller shaft RPM and power.

Temperature, DO, and conductivity profiles were measured in situ using a Martek Mark V Digital Water Quality Analyzer (Figure 13). A malfunction in the pH circuit made it necessary to determine the pH in the laboratory using a Sargent-Welch Model NX digital pH meter. The Martek instrument was checked weekly using the Azide modification of the Winkler method of determining DO as stated in Standard Methods (36).

Water samples were obtained at various depths using a Kemmerer water sampler (Figure 14).

Clarity readings were taken in situ using a Wildco 20 centimeter

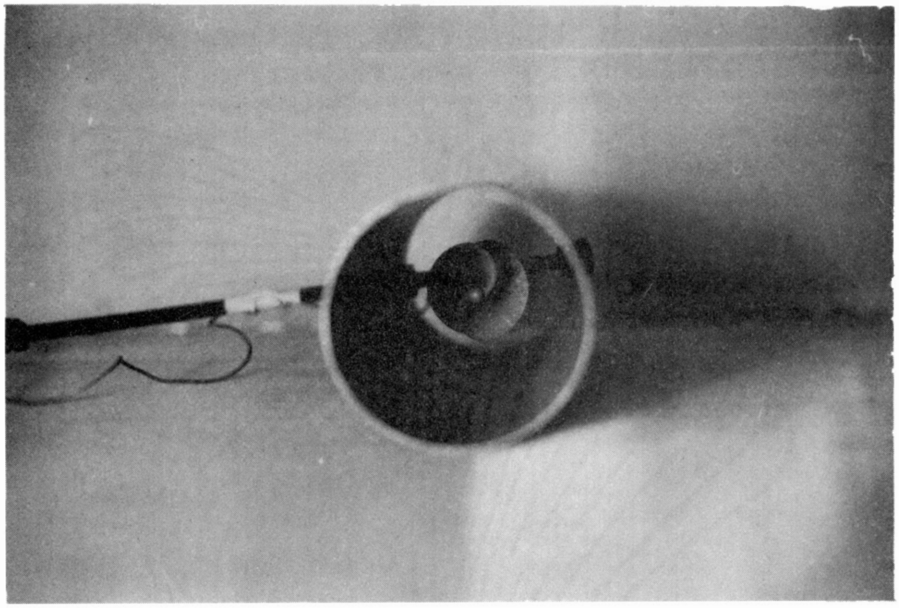
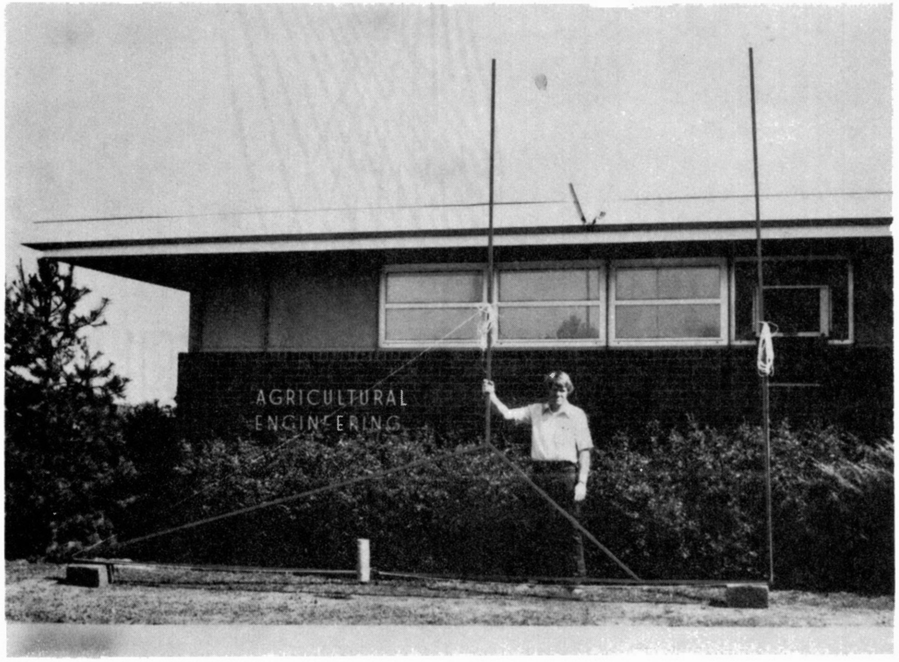


Figure 11. Current Meter Propeller in Conduit



Fiture 12. Current Meter Traversing Mechanism

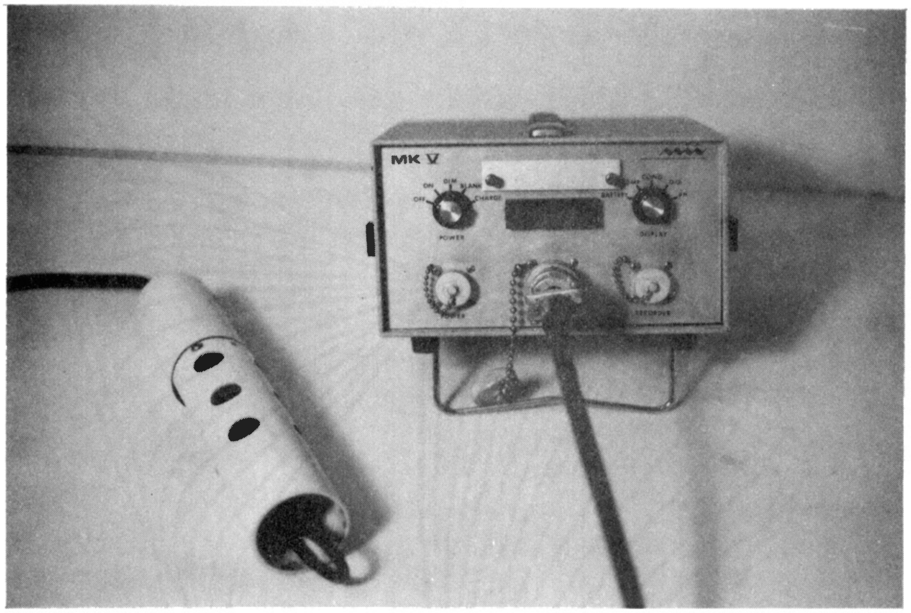


Figure 13. Martek Water Quality Analyzer

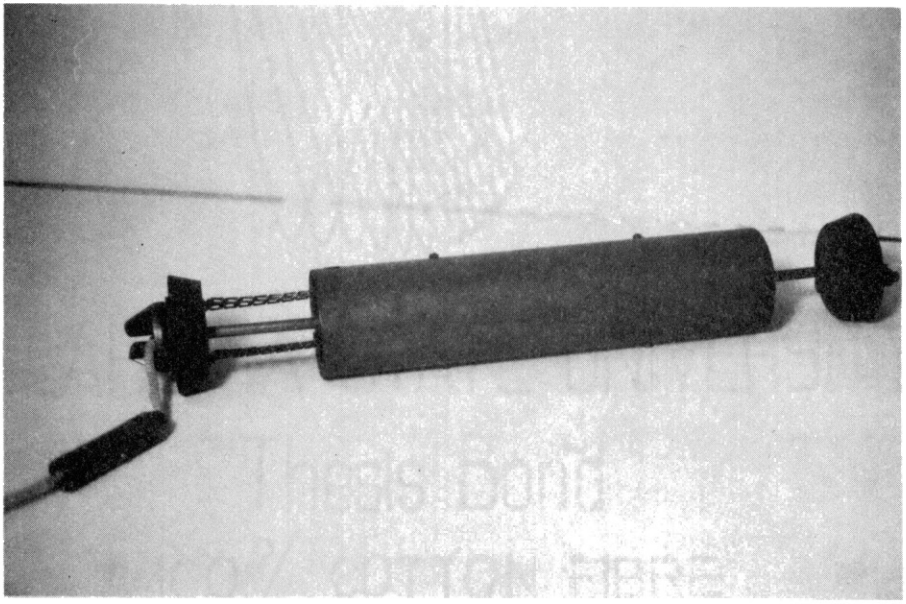


Figure 14. Kemmerer Water Sampler

plastic secchi disk.

Iron, manganese, and turbidity concentrations were measured in the laboratory using a Coleman Model 6C Junior Spectrophotometer.

All weighing for the solids test was done on a Mettler Type H6 analytical balance.

Location of Equipment

Ham's Lake is an upstream floodwater detention reservoir of the Soil Conservation Service located about eight kilometers west of Stillwater, Oklahoma. The lake has a surface area of almost 40 hectares, a maximum depth of about 9.5 meters, and a volume of 115 hectare-meters when at principal spillway elevation of 287 meters above sea level. A map of the lake profile is shown in Figure 15. Area and capacity curves are shown in Figure 16. Although it is a relatively shallow lake, it does exhibit thermal and chemical stratification. Oxygen stratification is very pronounced. During summer the surface water is supersaturated while the DO goes to zero between the three and four meter depths.

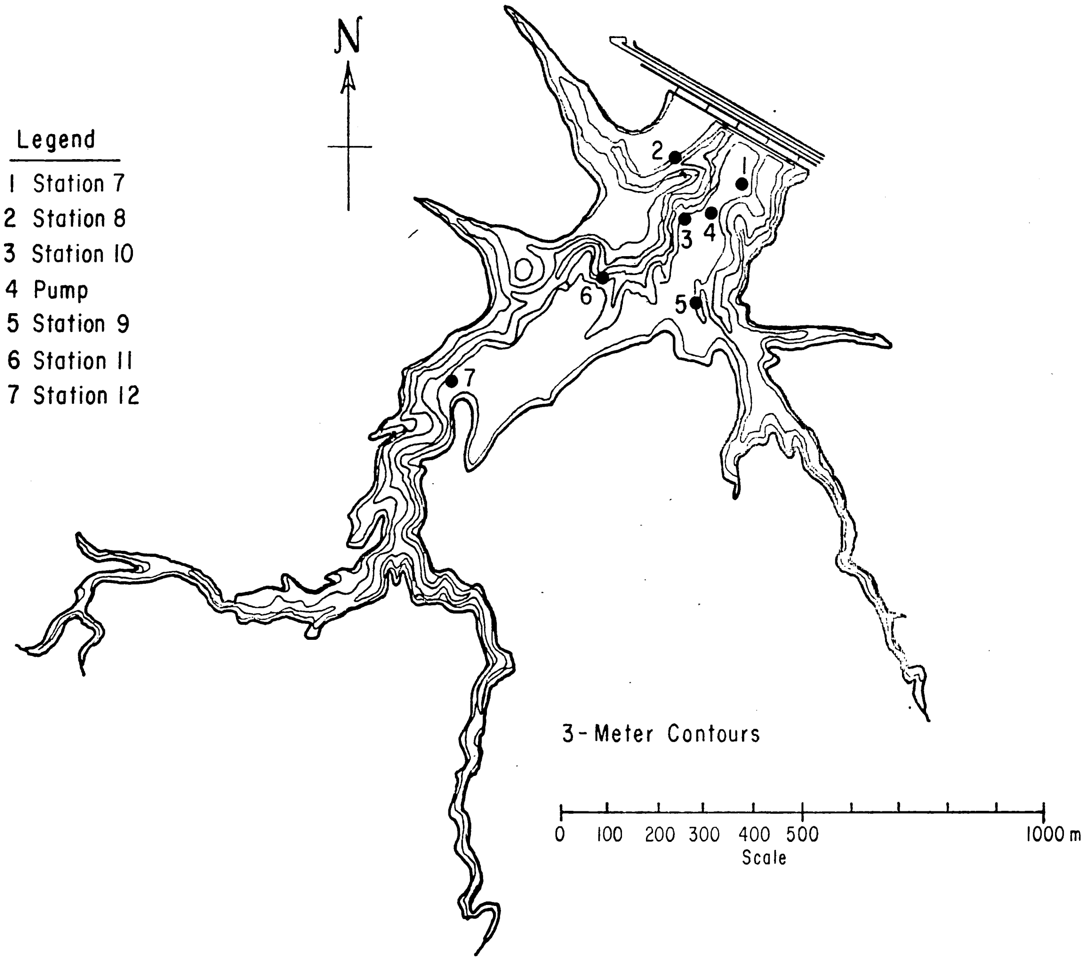


Figure 15. Map of Ham's Lake Showing Sampling Locations

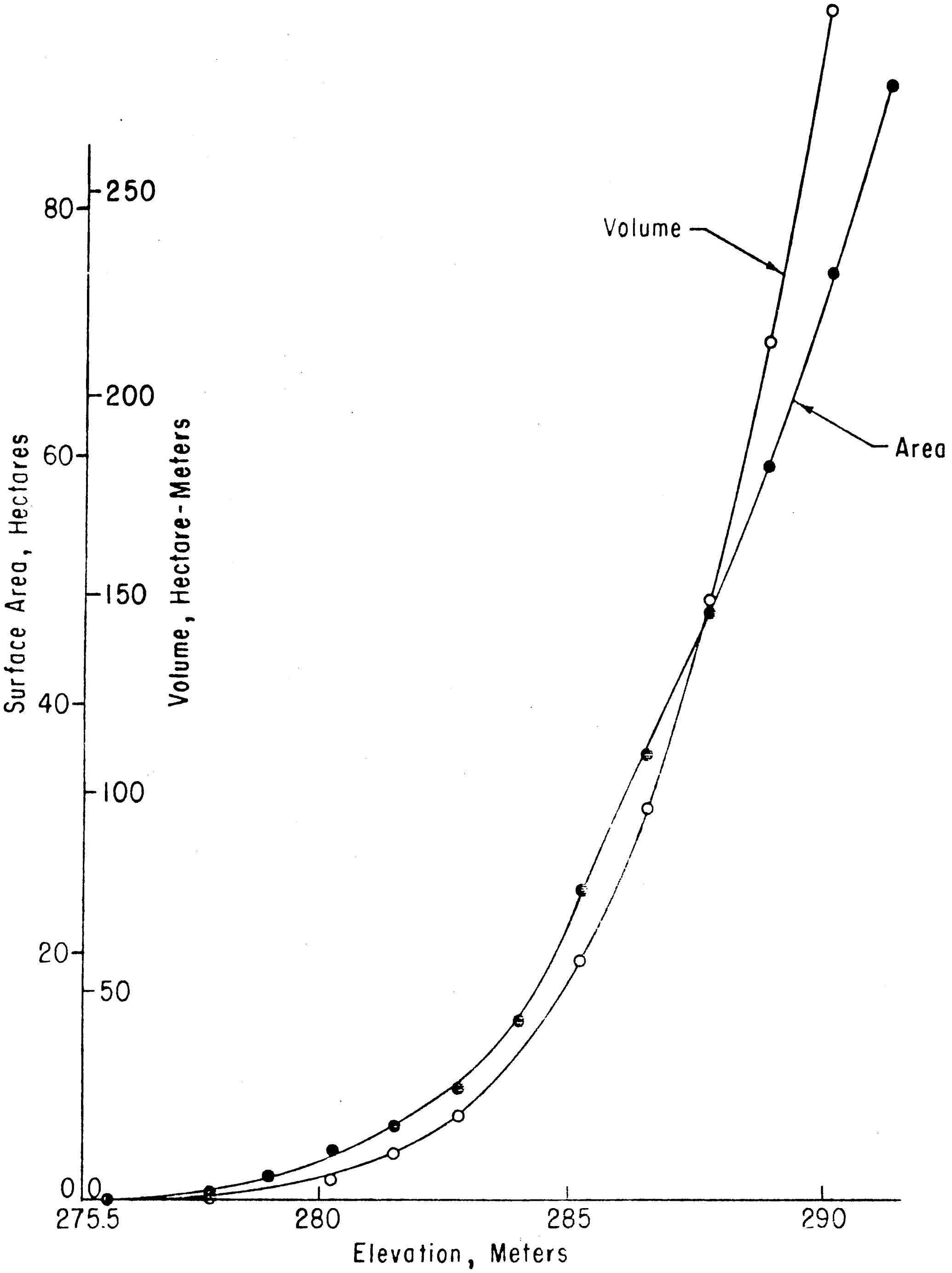


Figure 16. Area and Volume Curves for Ham's Lake

CHAPTER IV

METHODS AND PROCEDURES

The objectives of this project were to design and construct a prototype low-energy lake destratifier, evaluate the performance and design of the pump when moving water under a low head, and determine its effect on water quality parameters.

The pump was constructed at the Agricultural Engineering Laboratory and transported to Ham's Lake. It was floated into position (Figures 17 and 18) and placed in operation on the morning of June 19, 1975. Stratification was well developed. The pump was operated continuously until October 15, 1975, except for shutdowns for minor repairs.

Physical-Chemical Measurements

To determine the pump's effects on water quality parameters, six sampling stations were located on the lake by floating buoys. Location of the pump and sampling stations is shown in Figure 15.

Partial preliminary data of temperature, DO, conductivity, pH, clarity, and BOD_5 were taken weekly from mid-February until the pump was put into operation.

DO, temperature, and conductivity readings were made at each station at one meter increments using the Martek instrument. These readings were made several times daily for the first three days of the

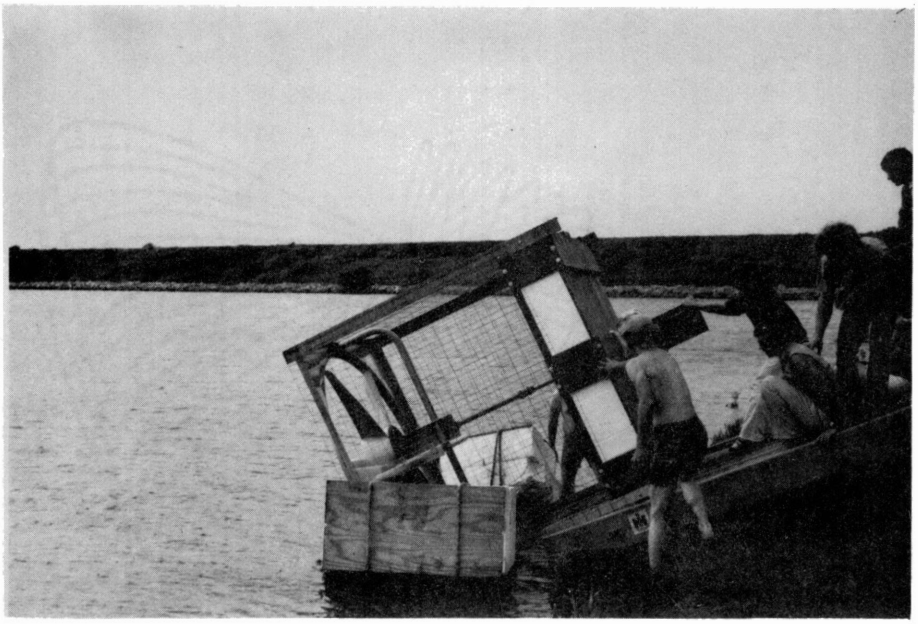


Figure 17. Unloading Pump at Lake

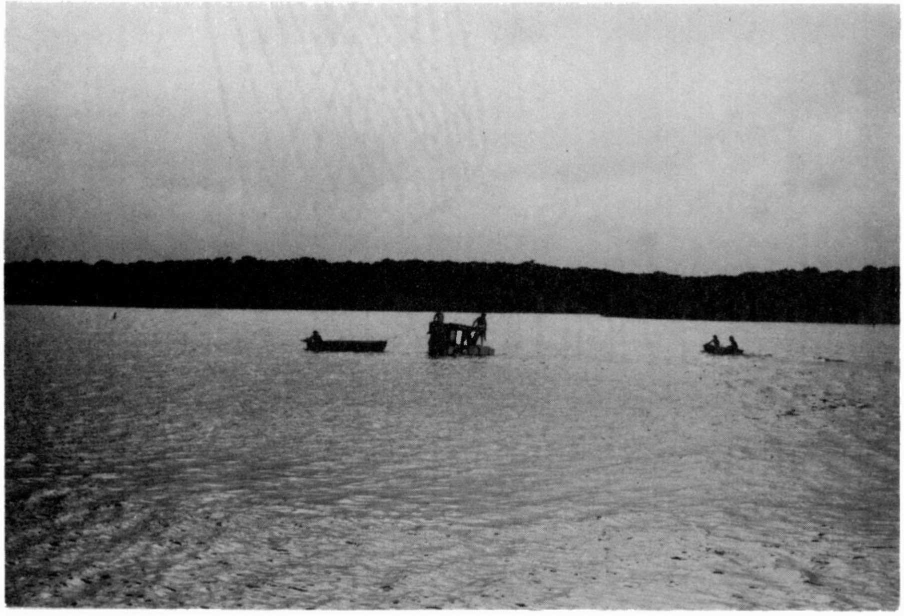


Figure 18. Pump Being Towed Into Position

pumps' operation and made daily until July 4. After this time readings were made three times weekly. Most of these readings were made in the morning between 9:00 a.m. and 11:00 a.m. The Martek instrument was checked weekly using the Winkler method for DO. The temperature and conductivity readings were checked monthly using a standard thermometer and a known concentration of potassium chloride solution at 25 °C.

Clarity readings were always taken at station 10, located approximately 50 meters west of the pump, and followed the same sampling schedule as DO, temperature, and conductivity.

BOD_5, COD, pH, alkalinity, turbidity, solids, iron, and manganese concentrations were determined in the laboratory from water samples taken using the Kemmerer water sampler. These samples were taken weekly at station 10 between 9:00 a.m. and 11:00 a.m., starting June 10. Samples were taken at depths of one, three, five, seven, and nine meters below the surface. Turbidity readings were made using a spectrophotometer and a calibration to Jackson Turbidity Units. Iron and manganese readings were made using a spectrophotometer and a calibration to known concentrations. All tests, except solids, were run in accordance to the procedures outlined in Standard Methods (36). CO_2 concentrations were determined by a nomograph (Figure 19), constructed by Steichen (4), using the pH and alkalinity measurements.

A procedure was developed by REA Engineering and Associates, Inc., for determination of the volatile solids in solution. This procedure was developed from their study of Lake Thunderbird in central Oklahoma (38).

Because water treatment plants using rapid-sand filtration cannot filter out taste, odor, or solids, a correlation was sought between

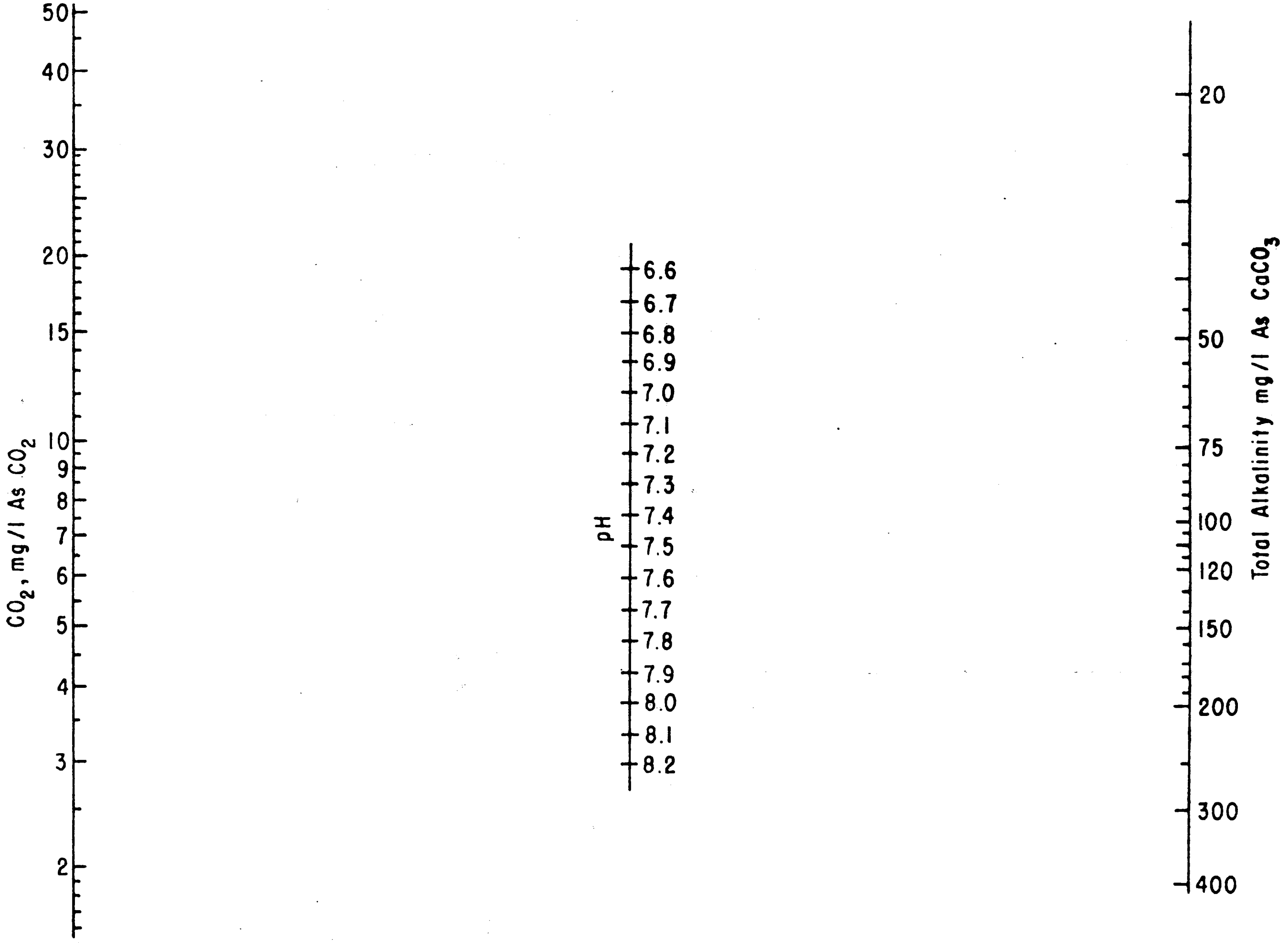


Figure 19. Nomograph for Calculating CO_2 from pH and Alkalinity (4)

dissolved solids and the taste and odor problems (38). They monitored dissolved solids at the inlet structure and found during the summer months volatile solids in solution were in the range of 70 to 80 mg/l. In the fall the lake turned over causing taste and odor problems. During this time volatile solids in solution rose to 150 mg/l. Within three weeks the volatile solids in solution had fallen to about 110 mg/l and taste and odor problems had disappeared. Thus it appears that taste and odor problems are related to a change in volatile solids in solution.

The procedure, developed from this study, to determine total solids, total suspended solids, total volatile solids, suspended volatile solids, and volatile solids in solution is shown in Table I.

Clarity, turbidity in Jackson Turbidity Units (JTU), and solids tests are all indications of the suspended material in the water. Clarity readings, which are taken in situ, give an indication of the depth light can penetrate into the reservoir. Turbidity indicates the optical property of a sample which causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. Water treatment plants use JTU as a measure of turbidity in the water. Solids test were run to determine which parts of turbidity were dissolved or suspended and which parts were fixed or volatile.

Mechanical Evaluation

Power input to the motor during operation was read to the nearest 10.0 watts. Using the calibration curve from the prony brake test a value of power output to the propeller shaft and RPM was determined.

Flow Measurement

Velocity readings were taken at 15.2 centimeter increments starting at the pump centerline and moving horizontal until the velocity approached zero. This procedure was duplicated at four, six, and eight meter depths using the traversing mechanism.

Total revolutions of the flow meter were measured over a five minute time interval. Three replications were taken for each velocity profile. The average number of revolutions for each position was calculated by taking a numerical average of the three values recorded. The average revolutions were converted to revolutions per second (rps) and velocity in meters per second (m/s) was calculated for each position using the manufacturer's calibration equation.

Difficulties Encountered

Difficulties encountered during the course of this research project are noted here to help alleviate problems future researchers might encounter when working in the area of artificial destratification.

Some type of lightening rod would be advisable for a destratifier unit floating in an open reservoir. Four separate times thunderstorms moving through the area caused the fuses in the electrical circuit to blow, causing short shutdowns of the pump.

It would be advisable to cover the sides of the raft with a fine meshed screen. Wildlife chewed on the exposed expanded foam.

Although the electric motor was totally enclosed, both bearings in the motor had to be replaced within four months. Replacement with sealed bearings should eliminate this problem.

A flashing light was mounted on the raft to prevent boats operating on the lake at night from colliding with it.

CHAPTER V

PRESENTATION AND ANALYSIS OF DATA

Data collected in this research project were used to determine the effect of the pump's operation on water quality parameters of a stratified reservoir and to evaluate performance and design of the pump when moving water under a low head.

Water Quality Parameters

Changes in water quality parameters were observed to determine if raw water quality of a reservoir was improved or degraded during artificial destratification with the down flow pump.

Temperature

It is well known that temperature and DO content in a reservoir vary during the year and with depth. During periods of stratification the natural oxygen demand of the dense water in the hypolimnion removes DO from solution.

Figure 20 illustrates the temperature changes that occurred at station 10, located about 50 meters west of the pump. Other locations showed similar changes. In mid-February the reservoir was isothermal at about 4 °C and warmed isothermally until mid-March. As atmospheric temperature increased in late March and through April the reservoir warmed at an exponential rate creating thermal stratification. On

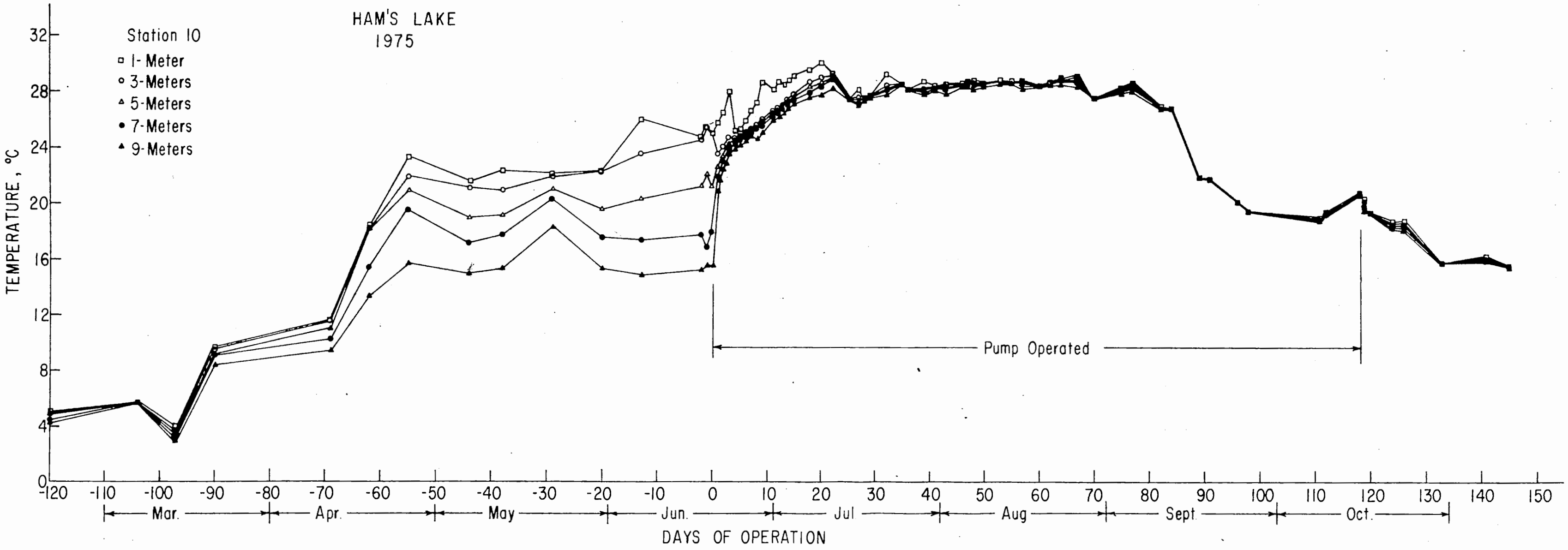


Figure 20. Temperature Versus Time at Station 10

June 6 there was a 12.7 °C temperature difference between the surface and the bottom. Several days of cooler, windy weather reduced this difference to 10.1 °C on June 18. Figure 21 illustrates the exponential rate of warming before pumping was started and the isothermal warming after thermal destratification was achieved. Isothermal cooling of the reservoir started in early September.

The short term effects of destratification on temperature are shown in Figure 22. Warming of the lower waters was at an exponential rate. The coldest water, at nine meters, warmed at the fastest rate. After one day of pumping the surface to bottom temperature difference had been reduced from 10.1 °C to 4.9 °C. After four days the difference had been reduced to 1.2 °C and the nine meter water temperature had increased 8.5 °C. The temperature profiles appear to pivot about the two meter depth, which is the approximate volume centroid for this reservoir. The June 27 profile is shown to illustrate a typical late afternoon temperature profile after thermal destratification was achieved. On a hot day the top two meters of water usually warmed slightly above the remaining depths. On a cloudy or cool day the profiles were almost isothermal.

Since destratification is dependent on breaking down the thermocline a plot of the density profiles is shown (Figure 23) to illustrate the pump's effectiveness in breaking the thermocline. The day before pumping began the thermocline existed between the four and seven meter depths. After one day's operation of the pump, the thermocline had risen between the two and three meter depths. After three days the thermocline was present between the one and two meter depths, and by the fourth day had completely disappeared.

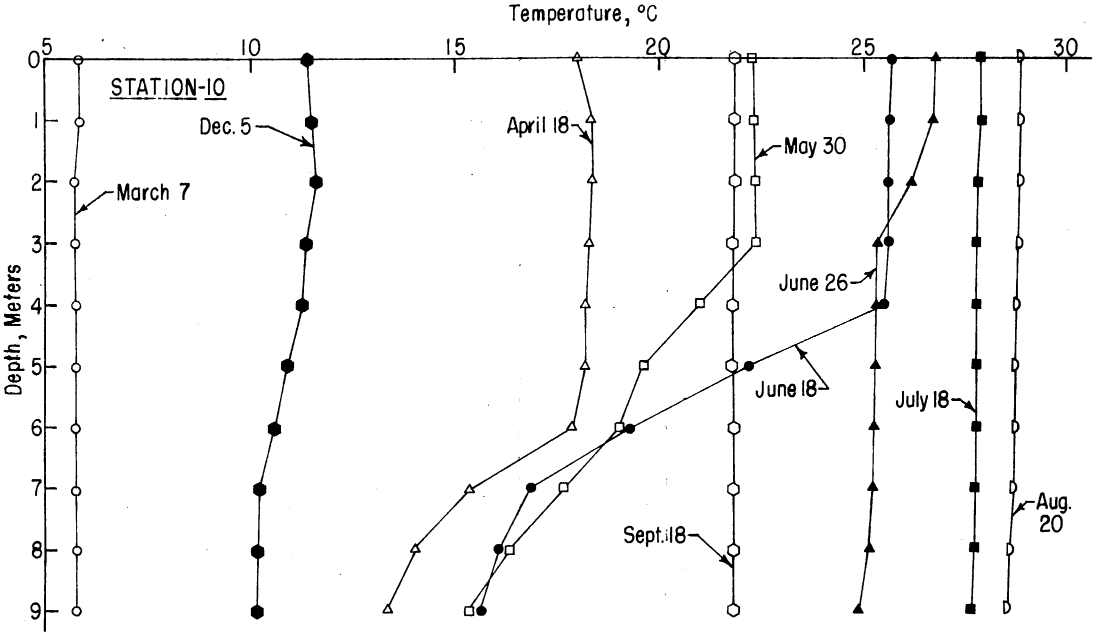


Figure 21. Selected Temperature Profiles at Station 10

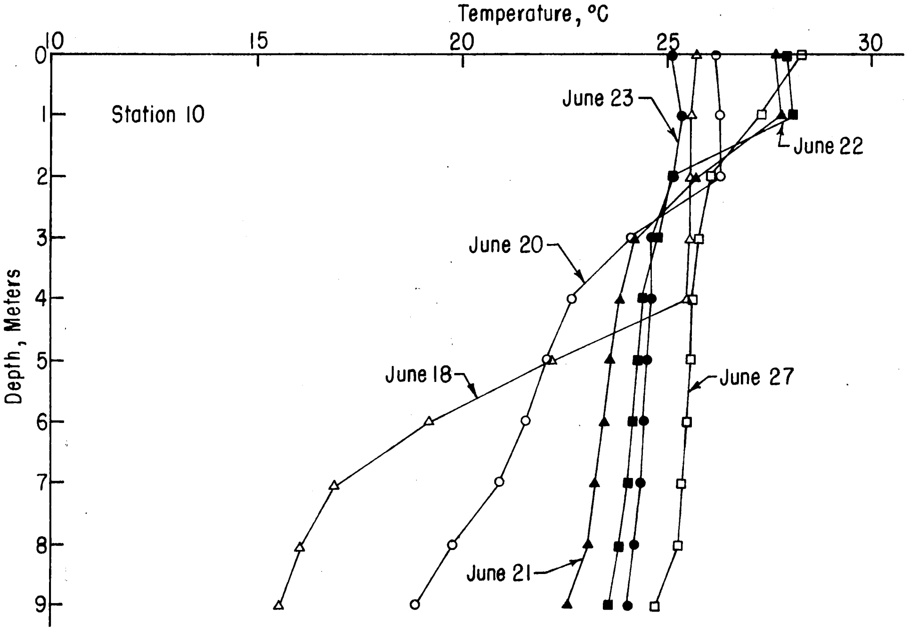


Figure 22. Short Term Effects on the Temperature Profile at Station 10

The pump was capable of warming the reservoir uniformly regardless of sampling location. Figure 24 illustrates this with six meter temperature readings taken at every sampling station. Station 12 located farthest from the pump, 675 meters southwest, did slightly lag behind the other stations. Other depths show similar results.

A plot of the surface temperature for this reservoir over the past four years is shown in Figure 25. The dashed lines indicate when a pump was operating. These data indicate very little, if any, cooling of the surface water occurred during destratification. Destratification was achieved by warming the bottom waters in the reservoir.

The Water Quality Criteria Committee of the Federal Water Pollution Control Administration (39) list temperature conditions which are considered to detract from raw water quality. The only detrimental effect of temperature resulting from this study was the increase in temperature of the hypolimnion waters. Some water impoundments use the colder water of the hypolimnion for cooling and for development of cold water biota.

Dissolved Oxygen

The changes in the regime are even more pronounced than temperature changes. Figure 26 illustrates the DO changes that occurred at station 10. In early March, DO often ranged as high as 10 to 11 mg/l at all depths. This level was due to the high rate of photosynthesis occurring and natural mixing in the reservoir. As thermal stratification developed, mixing in the deeper waters was cut off by the thermocline. Since no mixing could take place DO could not be replenished and the natural oxygen demand lowered the DO. By mid-May

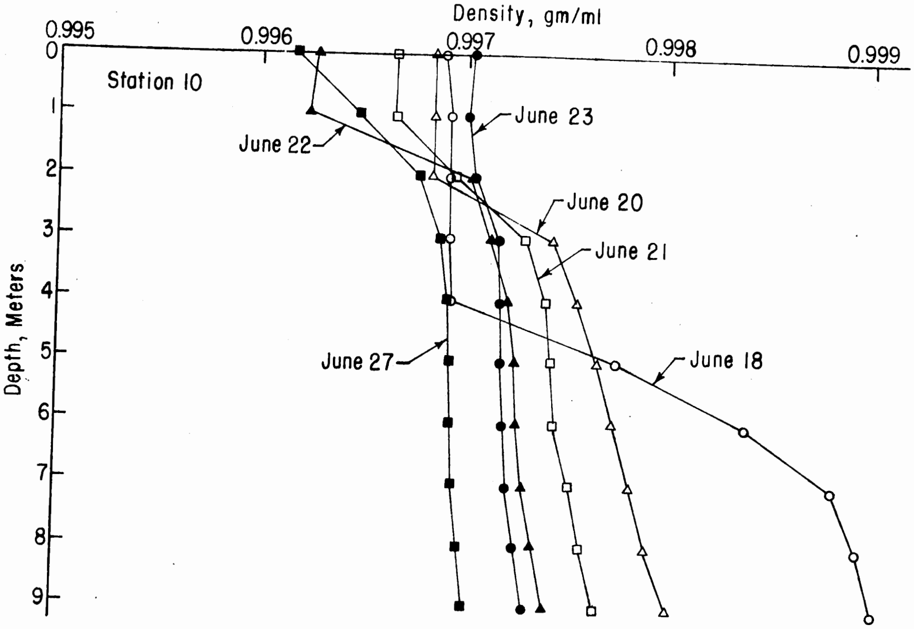


Figure 23. Density Profiles at Station 10

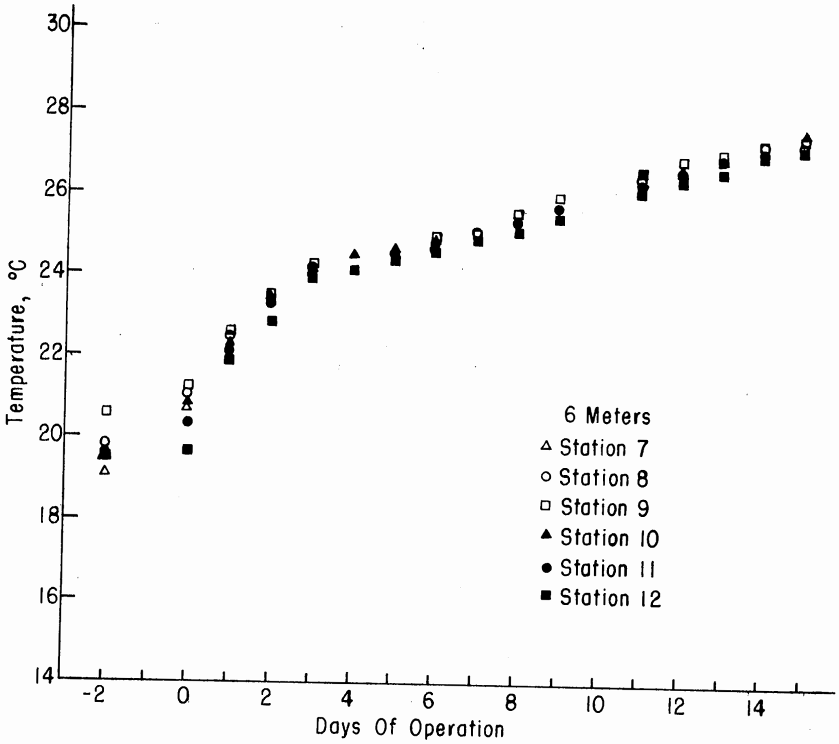


Figure 24. Temperature Versus Time for Readings Taken at the Six Meter Depth for All Sampling Locations

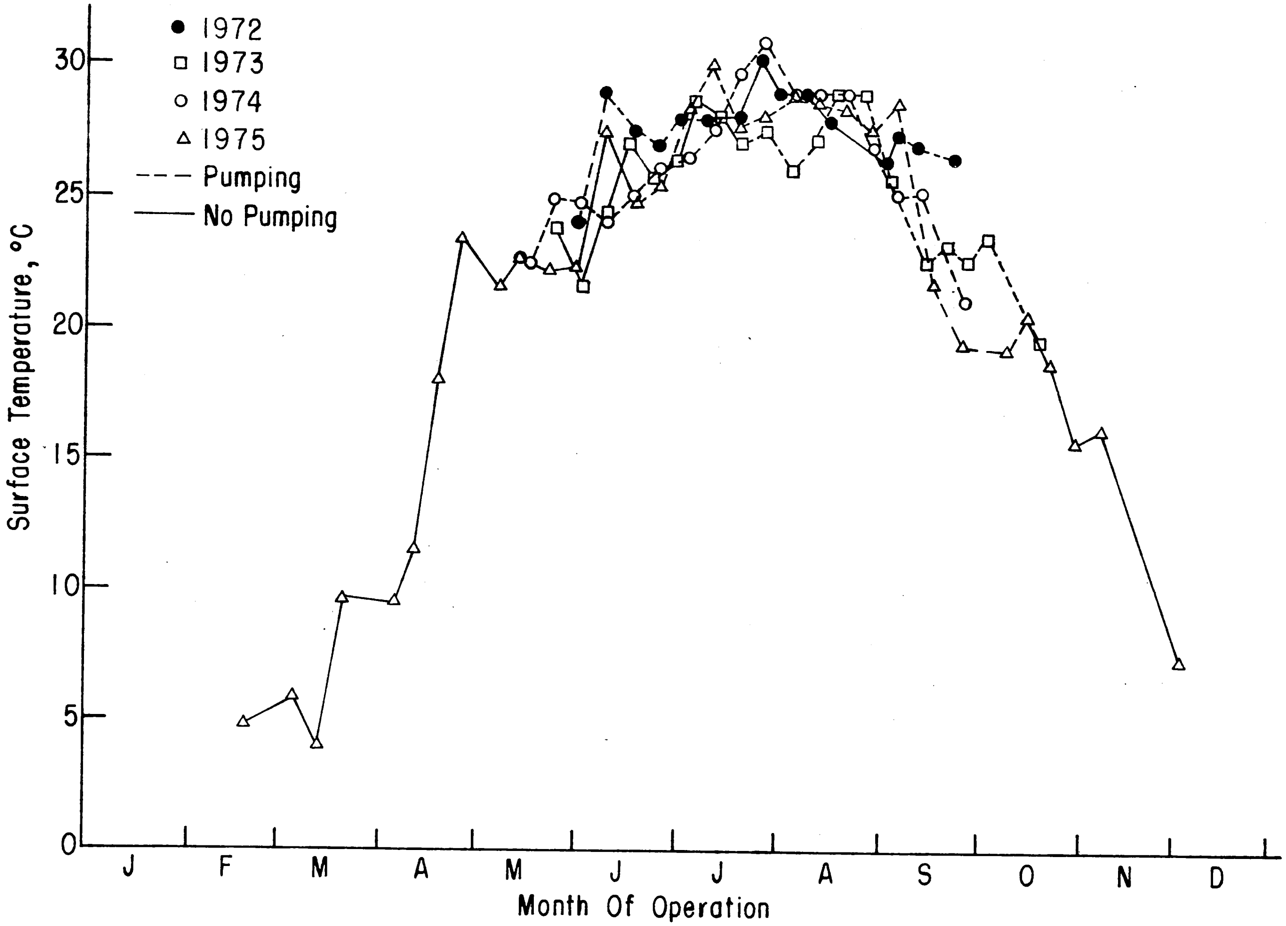


Figure 25. Surface Temperature Versus Time for Ham's Lake from 1972 to 1975

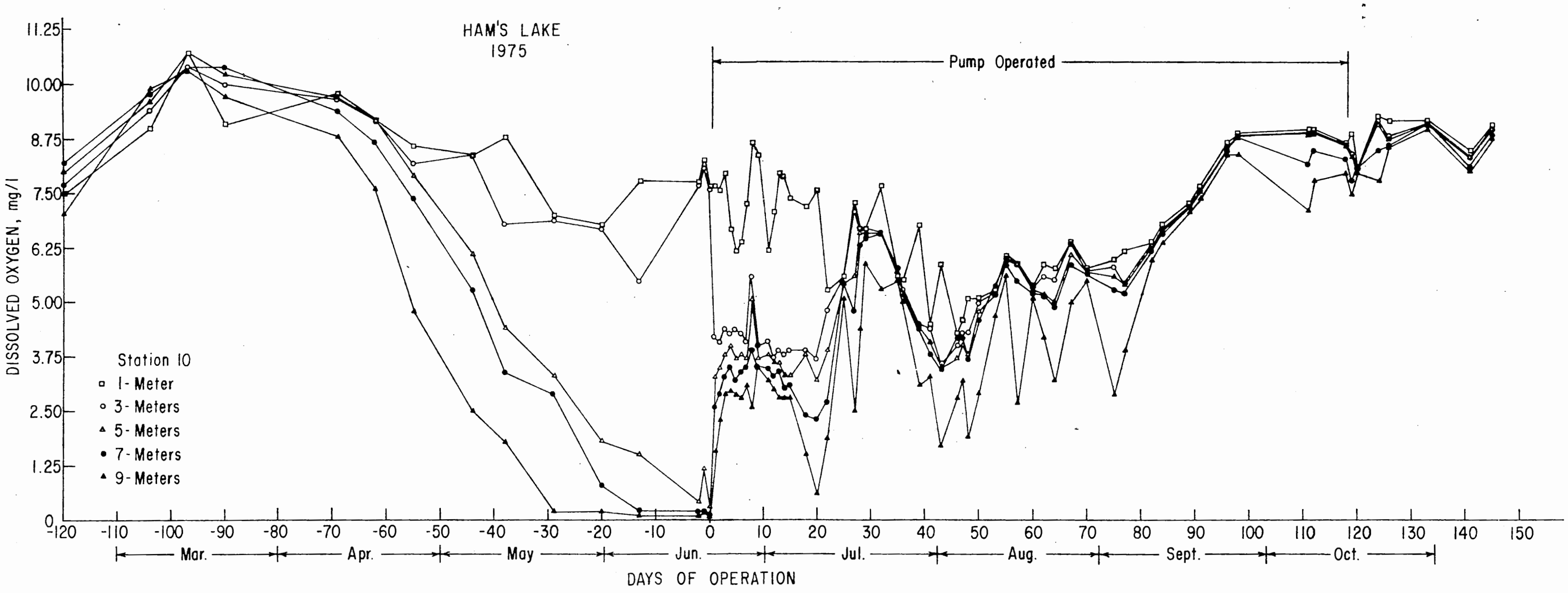


Figure 26. Dissolved Oxygen Versus Time at Station 10

DO was essentially zero at nine meters. DO in the lower waters continued to be depleted and by mid-June DO was essentially zero below four meters. The decrease in DO in the epilimnion waters before pumping was started was probably caused by increased respiration and other processes which are dependent on temperature. According to van t'Hoff's law (13) oxidation rate is doubled to tripled by a temperature rise of 10 °C. Between early March and late May the epilimnion waters had increased about 20 °C.

Figure 27 shows changes in DO profiles as stratification developed and the effects after mixing. These profiles correspond to temperature profiles shown in Figure 21.

Figure 28 shows the immediate effects of pumping on the DO profile. The day before pumping began DO below five meters had been depleted of oxygen and water above four meters had in excess of 8.0 mg/l. After one day of pumping, DO at five and nine meters had increased to 3.3 and 1.9 mg/l, respectively. DO at three and four meters had been reduced to about 4.0 mg/l and DO above three meters was slightly reduced. On June 23, the first day that the temperature profile was entirely uniform, DO ranged from 7.2 mg/l at the surface to 2.9 mg/l at the bottom. DO continued to decrease in the upper waters as DO increased in the lower waters. On July 14, DO was between 5.0 and 6.0 mg/l at all depths. Reduction in DO of the upper waters was probably caused by mixing the surface waters with the high oxygen demand water of the hypolimnion and its relative increase in temperature.

A decrease in DO of the surface water allows more efficient use of the photosynthetic oxygen produced. Steichen (4) reported readings

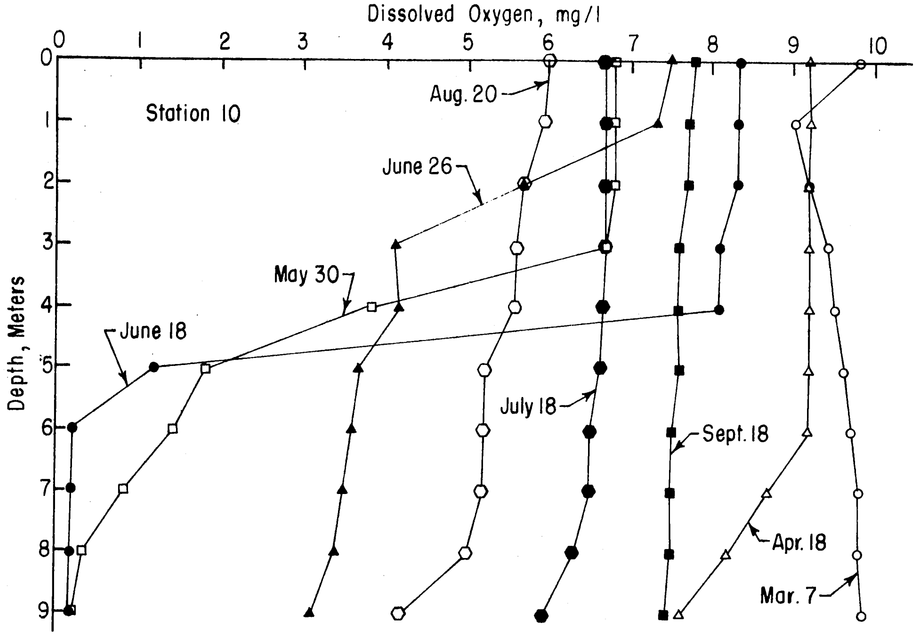


Figure 27. Selected Dissolved Oxygen Profiles at Station 10 During 1975

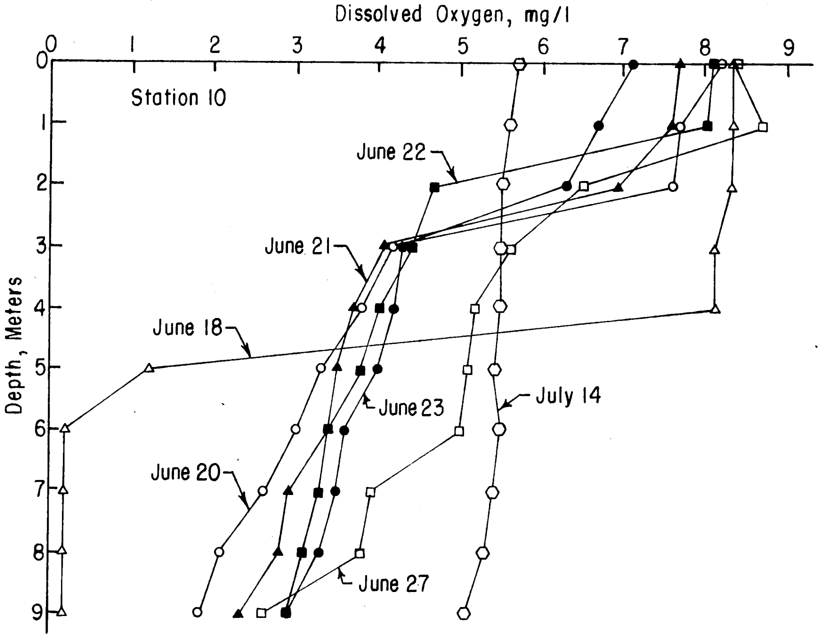


Figure 28. Short Term Effects of Destratification on the Dissolved Oxygen Profile at Station 10

of DO at sunset as high as 10 to 11 mg/l at the surface. Under such conditions, oxygen is lost to the atmosphere. A reduction of surface oxygen concentration below saturation allows the atmosphere to become an additional oxygen source instead of an oxygen sink.

After the DO profile became constant on July 14, a reduction in DO was again resumed. The DO profile continued to decrease until July 30 when the surface reached its lowest value of 4.6 mg/l. The following day the nine meter reading reached its lowest value of 1.9 mg/l. After this, DO increased until the fall turnover. The nine meter reading consistently lagged the other depths but never fell below 1.9 mg/l.

Figure 29 illustrates how DO varied with sampling location at the six meter depth. Two days prior to pumping, all stations showed about the same DO concentration. After a few hours of operation the difference between stations ranged from 0.2 to 3.6 mg/l. The stations located farthest from the pump, stations 11 and 12, generally lagged slightly behind the other stations, but a general increase in DO at all stations was noted.

Permissible surface water criteria for public water supplies (39) states that mean monthly DO should be $\geq$ 4.0 mg/l and any individual sample should be $\geq$ 3.0 mg/l. At no time did the surface DO fall below these values.

For a diversified warm water biota, DO concentration should be above 5.0 mg/l but may range between 4.0 and 5.0 mg/l for short periods during any 24-hour period. Figure 30 shows the percent of lake volume containing in excess of 5.0, 4.0, and 3.0 mg/l of DO.

Raw data of temperature and DO profiles were too numerous to make direct analyses of day-to-day changes practical. A computer program,

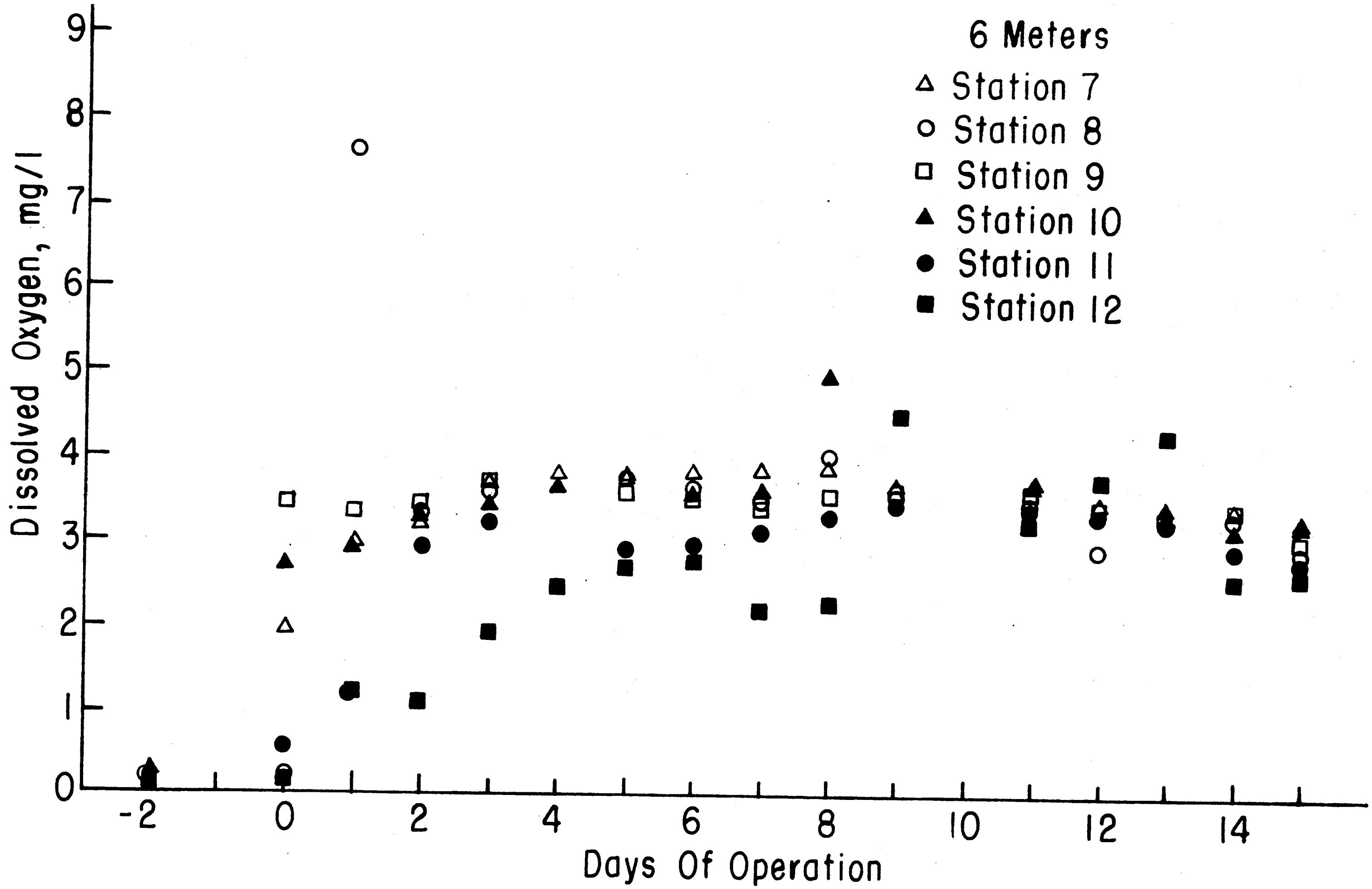


Figure 29. Dissolved Oxygen Versus Time for Readings Taken at the Six Meter Depth for All Sampling Locations

Table II, was developed which reduced this data to a few parameters for each day. The parameters calculated were the lake's elevation, volume, and surface area, centroid elevation, weighted average temperature, weighted average DO, total mass of DO, stability index and oxygen distribution index (Table III). The weighted averages were calculated taking into account the area at the top and bottom of each slice to obtain an average for each slice. Each of the slice averages were then weighted by volume to obtain an average for the entire reservoir.

Changes in weighted average temperature and DO are shown in Figure 31. Average temperature was observed to increase both before and after mixing until it reached a maximum value of 29.5 °C on July 9. Following this maximum value the average temperature decreased and remained relatively constant between 28 and 29 °C until the reservoir began to cool in early September. Average DO varied between 5.0 and 7.0 mg/l before mixing but most of the DO was in the top four meters of water. Immediately after pumping started the average DO began decreasing because of the distribution of the upper water DO throughout the entire reservoir and the high oxygen demand water brought up from the hypolimnion. However, DO was present throughout the water column. In mid-July average DO increased to its value just prior to mixing and then decreased until it reached its lowest value of 4.3 mg/l on August 4. After this time average DO increased until the natural turnover occurred in early September.

pH, CO_2, and Alkalinity

Within the phototrophic stratum both the rooted aquatics in the littoral zone and the microscopic algae of the open water plankton

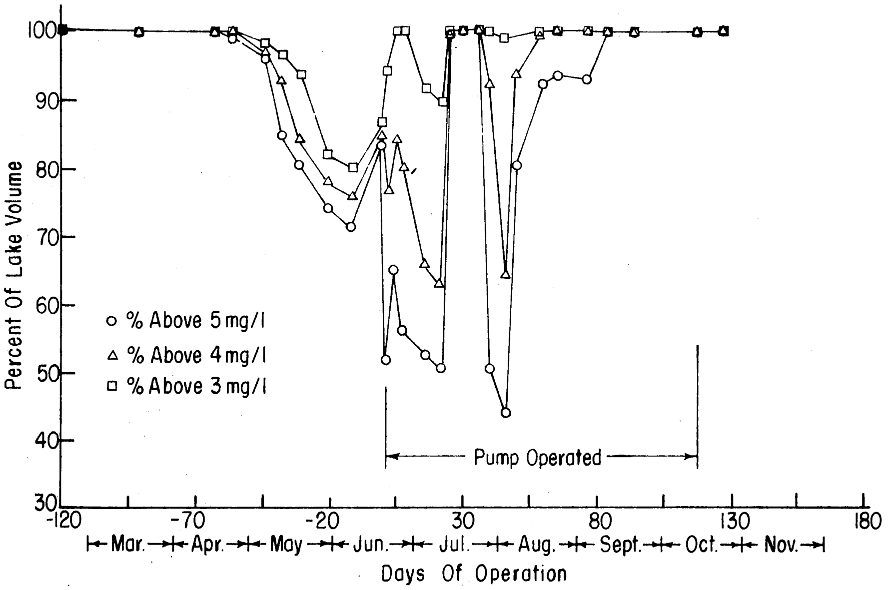


Figure 30. Percent of Lake Volume Versus Time for Dissolved Oxygen in Excess of Five, Four, and Three Milligrams Per Liter

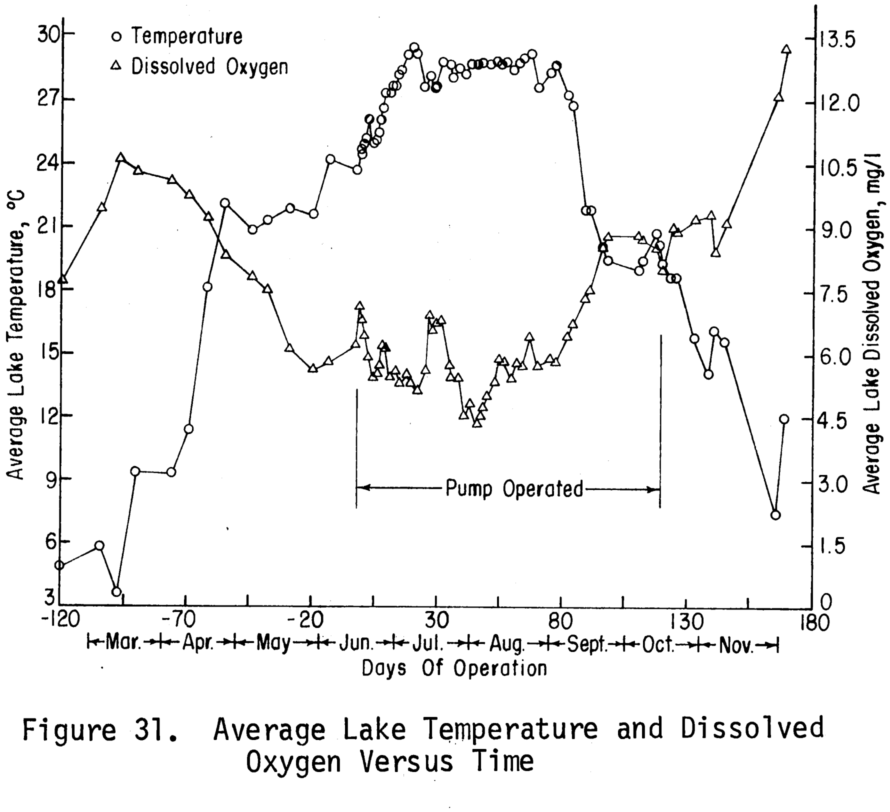


Figure 31. Average Lake Temperature and Dissolved Oxygen Versus Time

combine with water and CO_2 or HCO_3 - by photosynthesis to produce oxygen and carbohydrates (sugar, starch), This process occurs during the day as soon as they begin to be active in the spring (13). As a result of photosynthesis the free CO_2 is reduced, calcium bicarbonate is reduced through precipitation of $CaCO_3$, and pH is increased.

In early spring CO_2, pH, and alkalinity were nearly uniform at all depths because of natural mixing (Figures 32, 33 and 34). As stratification developed in late spring, hypolimnion waters were cut off from natural mixing. Since light could not penetrate into the hypolimnion, little photosynthesis occurred and respiration released CO_2. This trapped CO_2 disassociates in water to form carbonic acid which resulted in a pH decrease.

Before mixing, CO_2 had disappeared at the surface and increased in the hypolimnion, pH was stratified ranging from 8.4 at the surface to 7.7 at the bottom, and alkalinity was slightly stratified ranging from 160 mg/l at the surface to 150 mg/l at the bottom.

The immediate effect of pumping was the return of CO_2 in the surface waters and an increase in the total water column. Surface water pH was reduced and the entire water column was about constant at 7.65. Alkalinity decreased in the surface water and increased in the hypolimnion, but remained between 150 and 160 mg/l. After this time pH increased until July 9 when the surface pH was 8.5 and at nine meters was 7.9. An algae bloom was observed on July 9. Following this bloom, pH decreased and remained relatively constant throughout the water column varying between 150 and 165 mg/l until the fall turnover.

Phenolphthalein alkalinity (Figure 35) was present at one meter

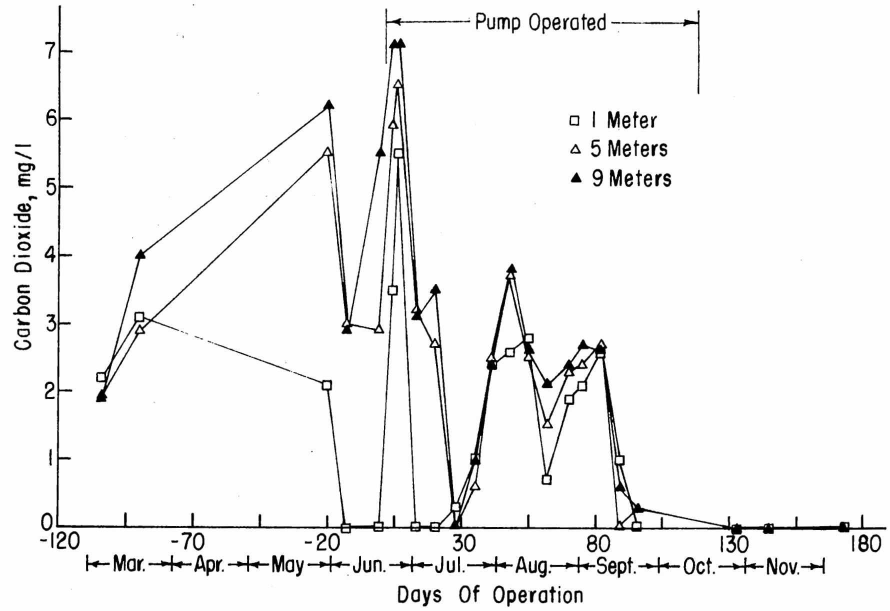


Figure 32. Carbon Dioxide Versus Time

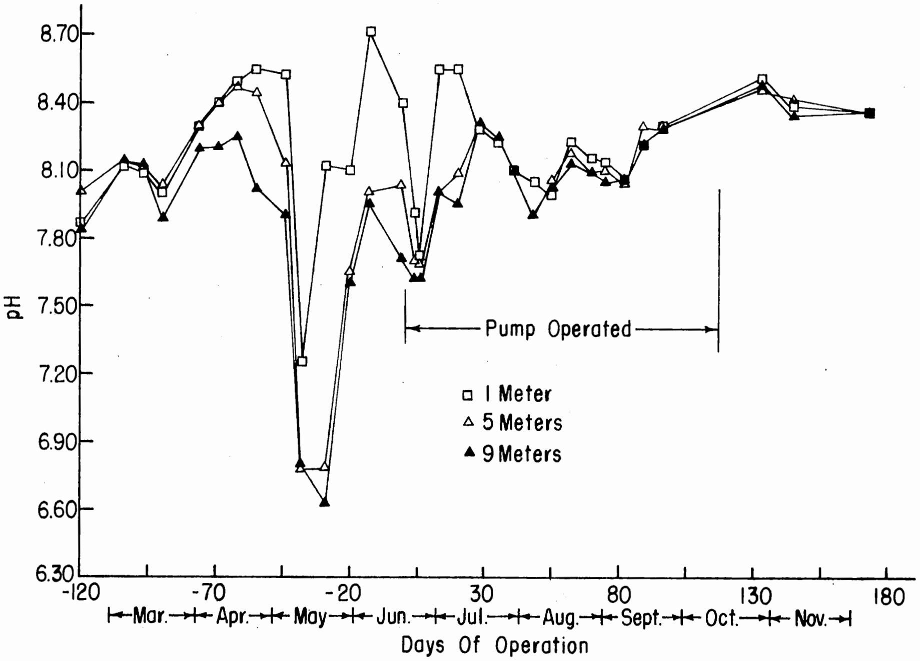


Figure 33. pH Versus Time

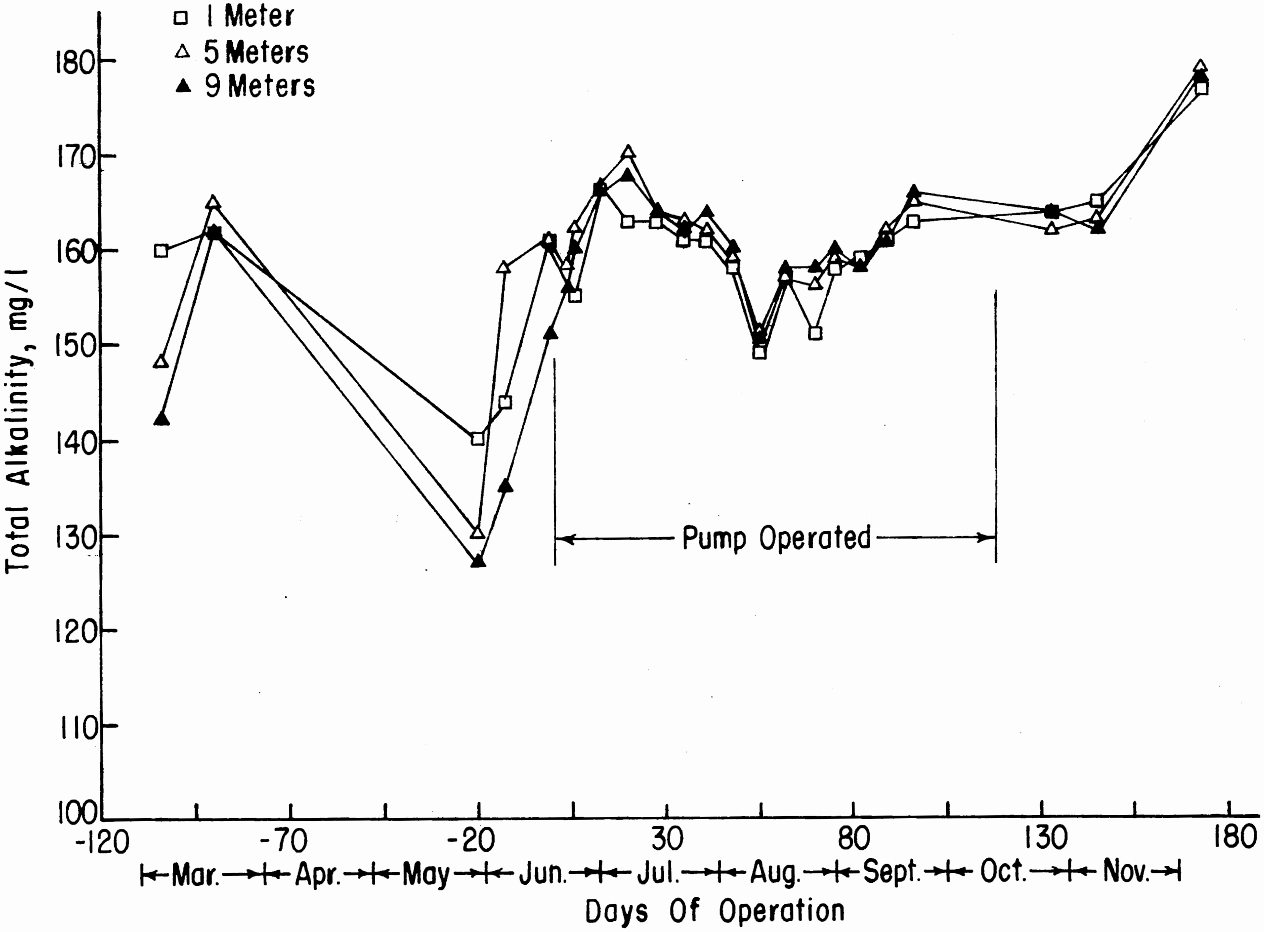


Figure 34. Total Alkalinity Versus Time

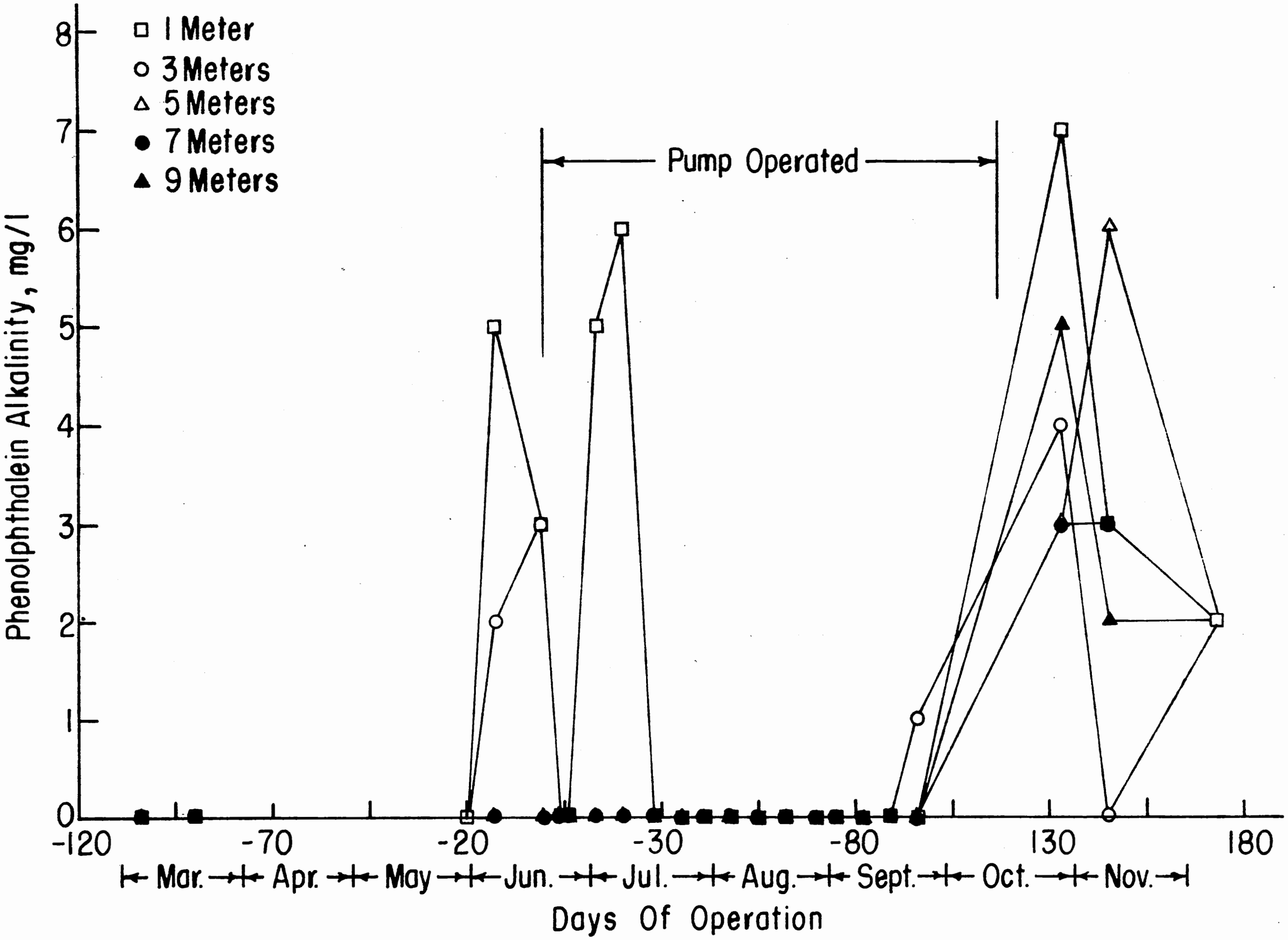


Figure 35. Phenolphthalein Alkalinity Versus Time

and sometimes at three meters from June 1 until mixing was started. Until late September, phenolphthalein alkalinity appeared twice after mixing in the top three meters of water. After late September it was present at all depths.

CO_2 reached its maximum value on June 25 when CO_2 varied from 5.5 mg/l at the surface to 7.2 mg/l at nine meters. On July 9, CO_2 was absent at the surface and was only 3.5 mg/l at nine meters. A week later CO_2 was almost absent in the entire water column. CO_2 then increased varying between 2.3 and 4.0 mg/l at nine meters and between 0.8 and 3.0 mg/l at the surface until the fall turnover.

Selected profiles of CO_2, pH, and total alkalinity are shown in Figures 53, 54, and 55, respectively.

Surface water criteria for public water supplies (39) states alkalinity should be in the range of 30 to 500 mg/l and pH in the range of 6.0 to 8.5. Recommendations considered satisfactory for aquatic life state pH should be in the range of 6.0 to 9.0, total alkalinity should not be less than 20 mg/l, and CO_2 should not exceed 25 mg/l. CO_2, alkalinity, and pH remained within allowable ranges during the pump's operation.

BOD_5 and COD

Biochemical oxygen demand (BOD_5) is usually defined as the amount of oxygen required by bacteria while stabilizing decomposable organic matter under aerobic conditions. Bacteria oxidize organic matter almost entirely to CO_2 and water.

Algal populations produce an oxygen demand. This demand takes three forms: (1) respiration that occur while photosynthesis is progressive, (2) respiration that occur at night when photosynthesis is absent, and (3) oxygen uptake caused by consumer organisms, mainly bacteria, that metabolize the algal bodies upon their death. These dead algae fall to the bottom increasing the organic load.

Changes that occurred in the BOD_5 are shown in Figure 36. Before mixing was started two BOD_5 blooms were observed. The first bloom occurred in mid-March when the one meter BOD_5 decreased to 2.2 mg/l, the five meter BOD_5 increased to 5.2 mg/l, and the nine meter BOD_5 increased to 4.5 mg/l. The second bloom occurred in early June when the BOD_5 increased to 6.2, 3.3, and 2.7 mg/l at one, five, and nine meters, respectively.

After mixing was started BOD_5 remained relatively constant throughout the water column varying from 0.5 to 1.5 mg/l the rest of the year. These relatively low values of BOD_5 indicated small amounts of biodegradable organic matter were present in the impoundment.

COD provides a measurement of the oxygen equivalent of that portion of organic matter in a sample that is susceptible to oxidation by a strong chemical oxidant (36).

Changes in COD are shown in Figure 37. COD values were relatively constant in the water column before and after pumping, except for the rise on July 9. Values normally ranged between 0.0 and 30.0 mg/l but increased to over 200 mg/l at one meter and above 80 mg/l at five meters on July 9. This date corresponded to the observance of an algae bloom and a pH of 8.5 at the surface. This indicated significant amounts of biologically resistant organic matter were present.

Selected profiles of BOD_5 and COD are shown in Figures 56 and 57.

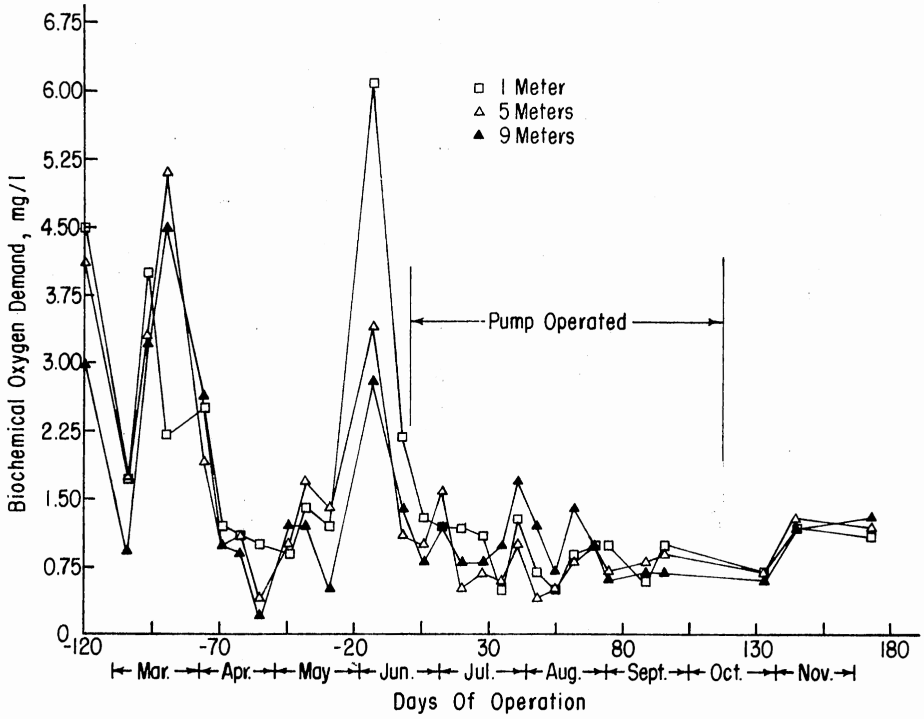


Figure 36. Biochemical Oxygen Demand Versus Time

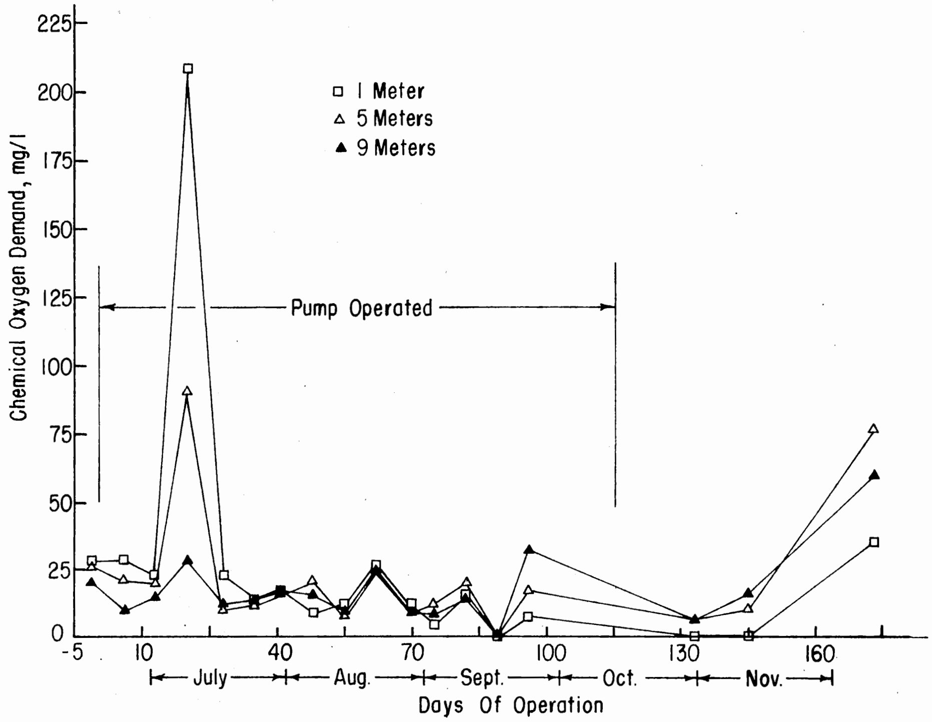


Figure 37. Chemical Oxygen Demand Versus Time

Specific Conductance

Specific conductance is a measure of a water's capacity to convey an electrical current. This property is related to the total concentration of ionized substances in a water and the temperature at which the measurement is made. Changes in specific conductance that occurred are shown in Figure 38. These readings are corrected to 25 °C. Prior to mixing, specific conductance varied considerably. The unusually low values in mid-May were probably due to heavy rainfall. The day before mixing began specific conductance varied from 380 micromhos per centimeter at the bottom to 460 micromhos per centimeter at the surface. After two days of mixing, specific conductance of the lower waters had increased to 440 micromhos per centimeter with the surface water decreasing to this value. Specific conductance remained constant throughout the water column at about 450 micromhos per centimeter during the remaining pumping period.

Selected profiles of specific conductance are shown in Figure 58.

Solids, Turbidity, and Clarity

Clarity measurements are presented in Figure 39. The low values in March and the big decreases in May were caused by heavy runoff from rain storms. After pumping was started clarity increased to 1.6 meters in early July. By mid-July clarity had decreased to 0.8 meters and remained between 0.7 and 0.9 meters until the fall turnover in early September. Desirable water quality criteria (39) for primary contact recreation state clarity should be a minimum depth of 1.2 meters.

The day before pumping began turbidity was stratified in the

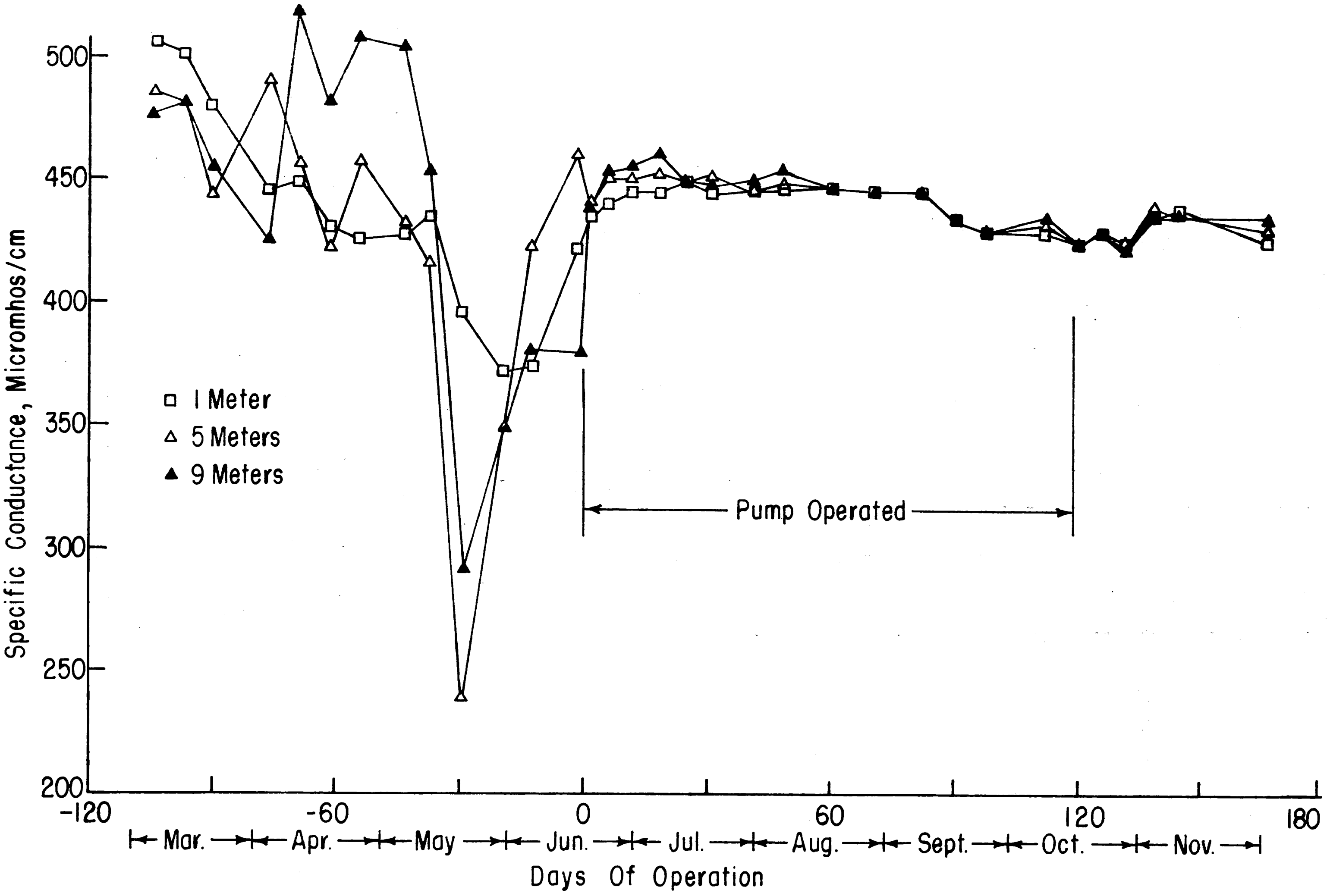


Figure 38. Specific Conductance Versus Time

reservoir (Figure 40). After a week of pumping turbidity at nine meters had decreased by almost half and slightly increased at the five meter depth. Turbidity measurements showed little change due to mixing after the first week and before the fall turnover. One meter measurements varied between 12 and 25 JTU and at nine meters varied between 20 and 35 JTU. Selected profiles of turbidity are shown in Figure 59.

There is no set turbidity criteria for water impoundments. However, water treatment plants are designed to remove the kind and quantity of turbidity to be expected in each water supply source. Therefore, any increase in turbidity and any fluctuating turbidity load over that normal to a water must be considered in excess of that permissible. Mixing appeared to maintain a more constant turbidity concentration throughout the reservoir.

Measurements of total solids and total suspended solids are shown in Figure 41. Total solids were nearly constant in the water column before and after mixing. Mixing tended to increase the total solids content with values ranging from 200 to 350 mg/l as compared to 200 to 250 mg/l before mixing.

Total suspended (filtrable) solids were stratified before mixing began. After a week of mixing, values at nine meters had been reduced from 28 to 10 mg/l and increased at five meters from 5 to 10 mg/l. Total suspended solids increased at all depths with continued mixing but never exceeded 25 mg/l. These low values of suspended solids indicated only a small portion of total solids present could be removed by water treatment plants.

Changes that occurred in total volatile and suspended volatile solids are seen in Figure 42. Mixing seemed to have little effect on

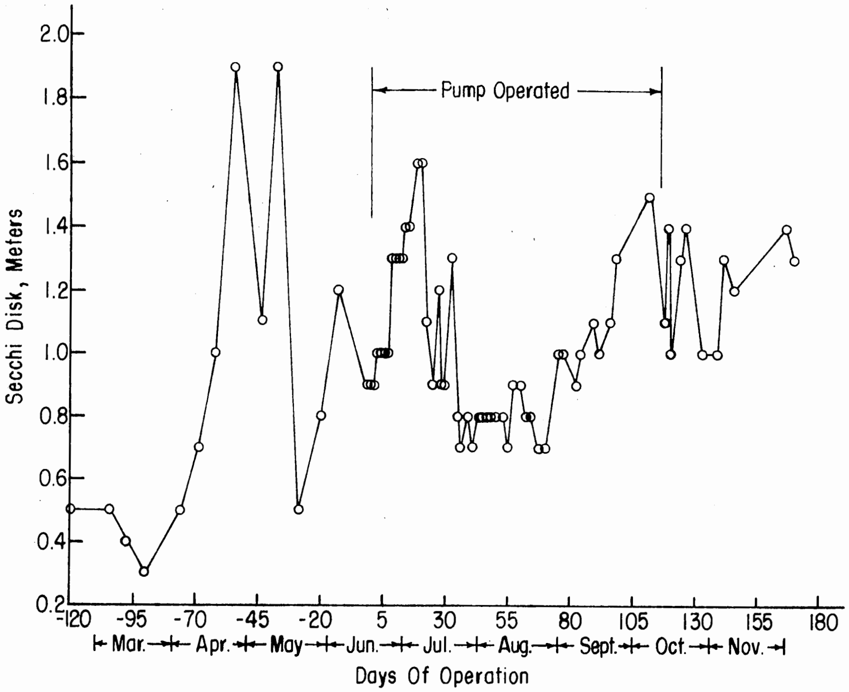


Figure 39. Clarity Readings Versus Time

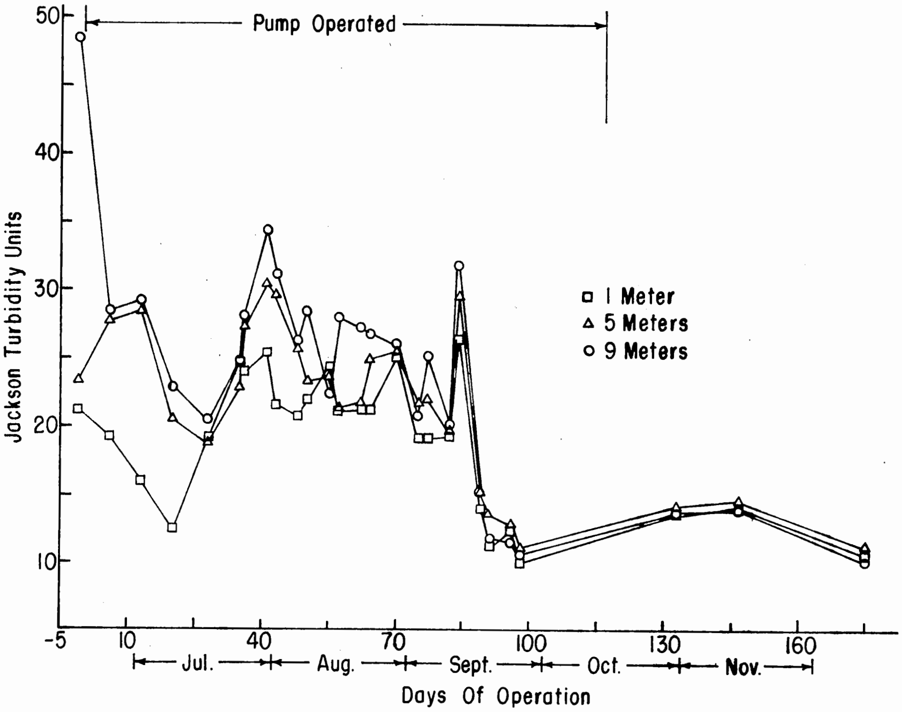


Figure 40. Turbidity Readings Versus Time

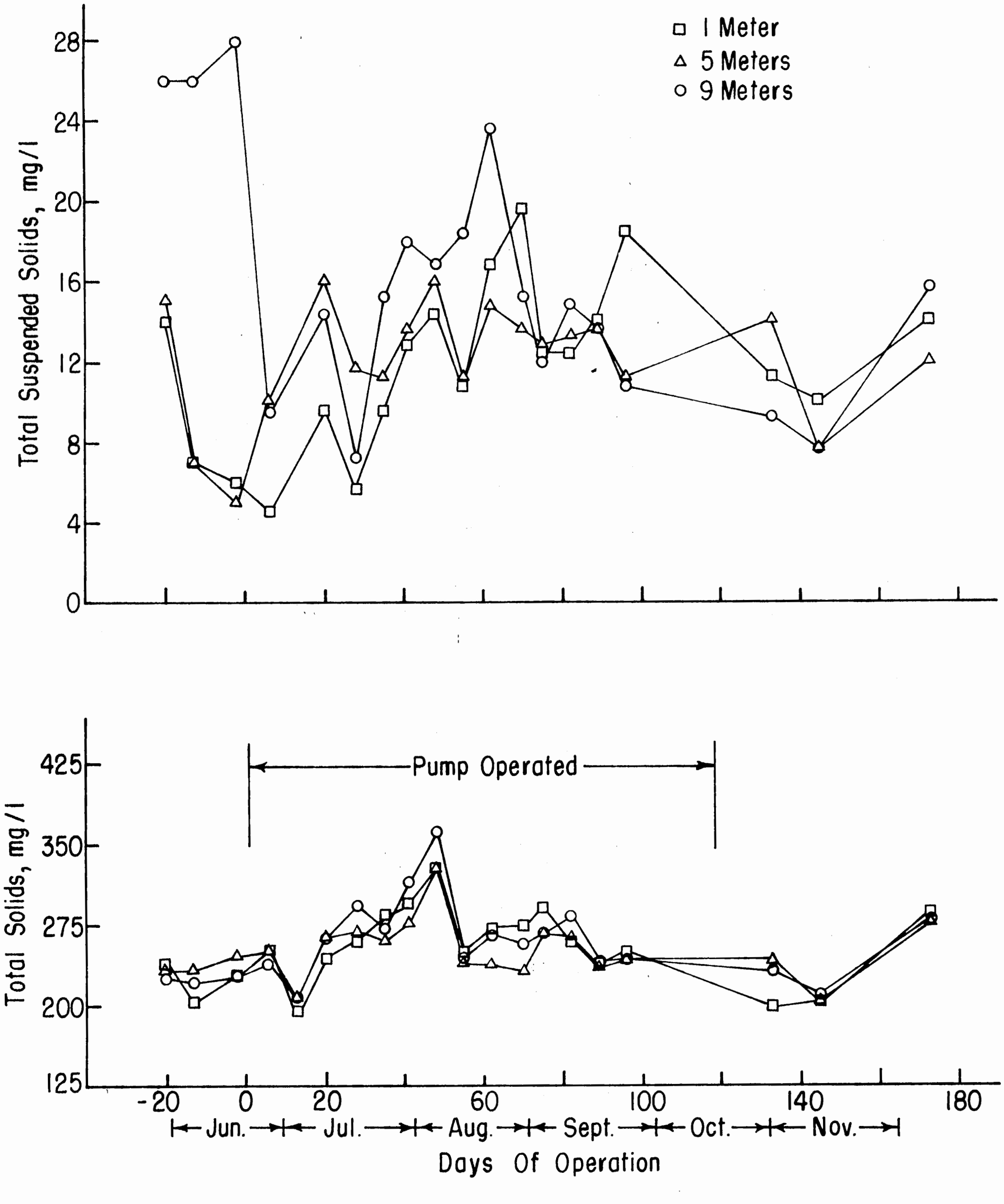


Figure 41. Total Solids and Total Suspended Solids Versus Time

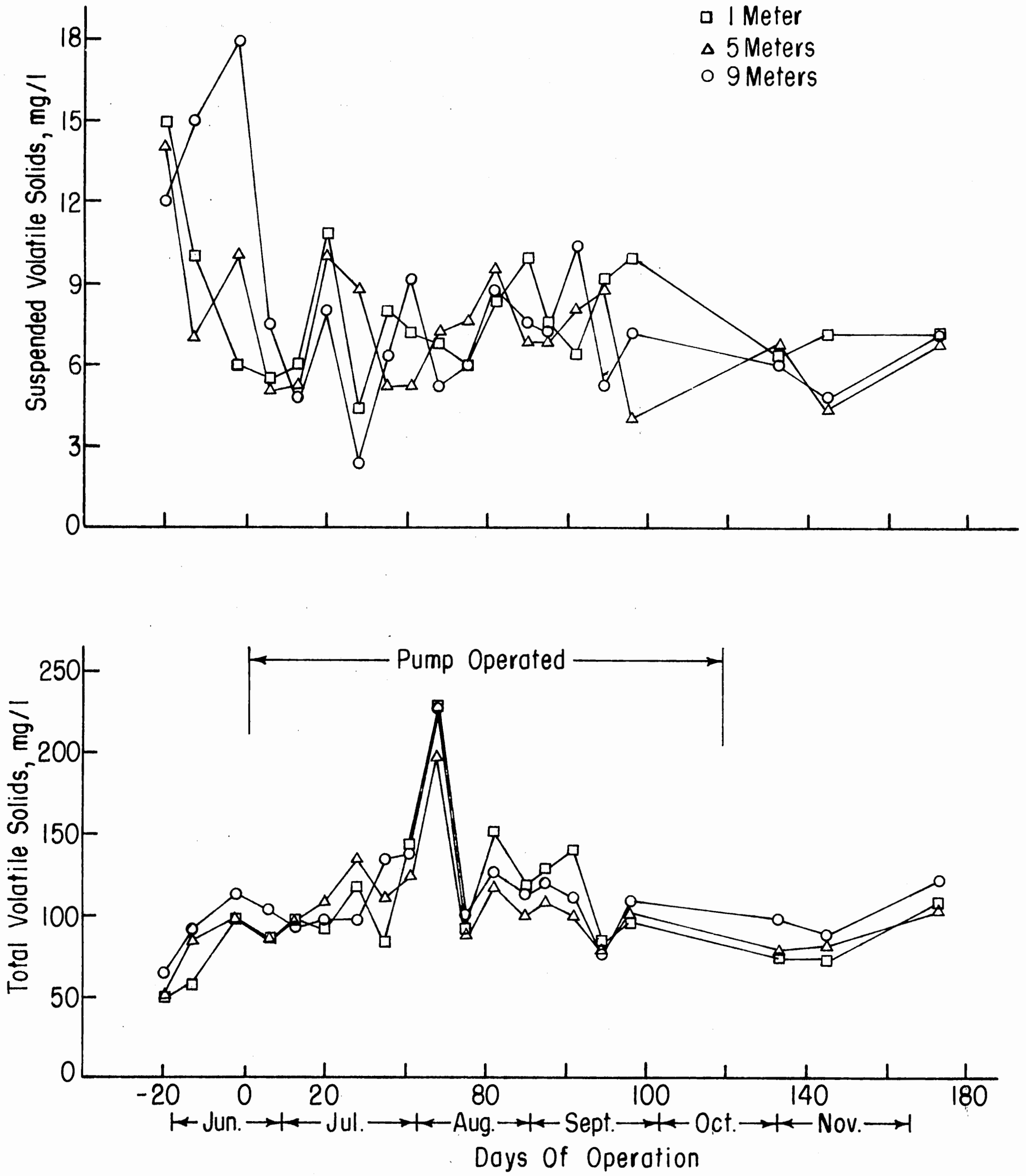


Figure 42. Total Volatile and Suspended Volatile Solids Versus Time

total volatile solids with values normally ranging from 80 to 150 mg/l. The major change that occurred was an increase in volatile solids in the surface waters and a corresponding decrease in the lower waters. A bloom occurring in early August did not correspond to a bloom of suspended volatile solids. This indicated the bloom was caused by an increase in dissolved volatile solids, which can be seen in Figure 43.

Suspended volatile solids were stratified before mixing began. Values varied from 6.0 mg/l at one meter to 18.0 mg/l at nine meters. Mixing introduced DO back into the lower waters allowing oxidation of the readily available organic matter which resulted in a decrease in these lower waters. An algae bloom on July 9 (20 days of operation) caused a slight increase at all depths, but decreased afterwards, and measurements ranged between 5 and 10 mg/l.

Before mixing, volatile solids in solution (Figure 43) measurements were less than 100 mg/l. After mixing, measurements normally varied between 75 and 130 mg/l but increased to about 200 mg/l in early August for a short period. Since taste and odor measurements were not taken it was not possible to determine if this sudden increase created taste and odor problems. The fall turnover in early September did not produce an increase in volatile solids in solution.

Selected profiles of total solids, total suspended solids, total volatile solids, suspended volatile solids, and volatile solids in solution are shown in Figures 60, 61, 62, 63, and 64, respectively.

The only surface water criteria (39) covering solids content permits a maximum total dissolved solids concentration of 500 mg/l. At no time were total dissolved solids observed to approach this maximum limit.

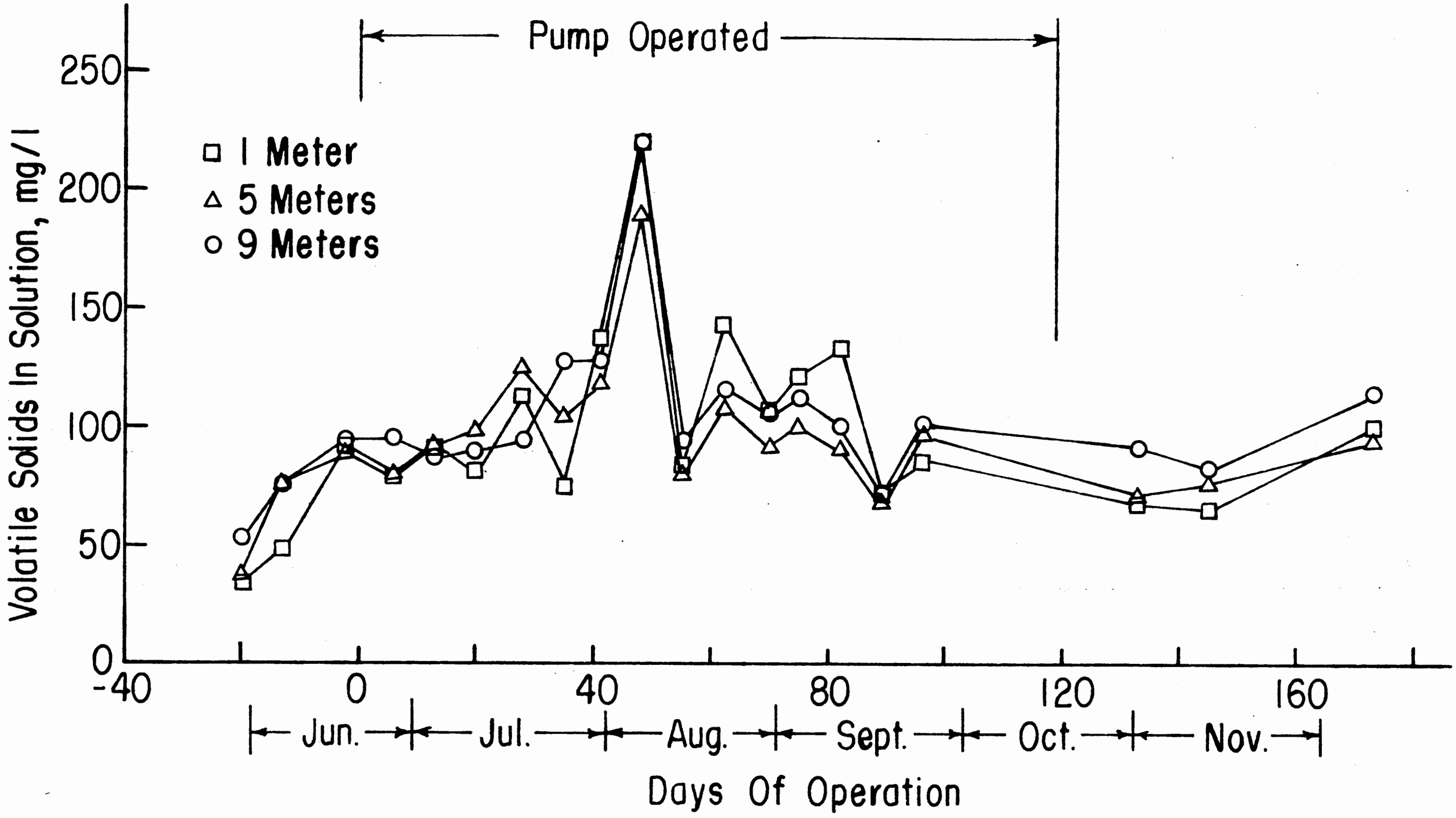


Figure 43. Volatile Solids in Solution Versus Time

Iron and Manganese

Iron measurements were not as encouraging as other parameters (Figures 44 and 45). Total iron concentration varied between 0.13 and 0.63 mg/l in the water column before mixing began. A week later iron concentration had decreased with the largest decrease occurring at nine meters. After this initial decrease, a general increase in total iron concentration occurred and reached a peak in early August. At this time, values ranged from about 0.9 mg/l at the surface to 0.44 mg/l in the lower waters. After early August, values ranged between 0.3 and 0.5 mg/l until the fall turnover. The general increase in total iron was possibly caused by circulation.

Filtrable iron measurements showed little change due to mixing. Before and after mixing values were normally less than 0.15 mg/l. The one meter reading did increase to 0.28 mg/l in late August but decreased shortly afterward. The fall turnover in early September increased the filtrable iron at all depths for a short period. Permissible surface water criteria (39) states a maximum limit of 0.3 mg/l for filtrable iron. Only after the fall turnover was this limit exceeded and this only occurred in the upper waters for a short period.

A general decrease in ferrous iron was observed with values normally below 0.15 mg/l. This decrease was caused by the presence of DO throughout the water column. Water can dissolve greater amounts of iron as ferrous bicarbonate when: (1) it is nearly free of DO, (2) it contains adequate amounts of CO_2, (3) the pH is not above 7.5, and (4) organic substances arising from decomposition are present which

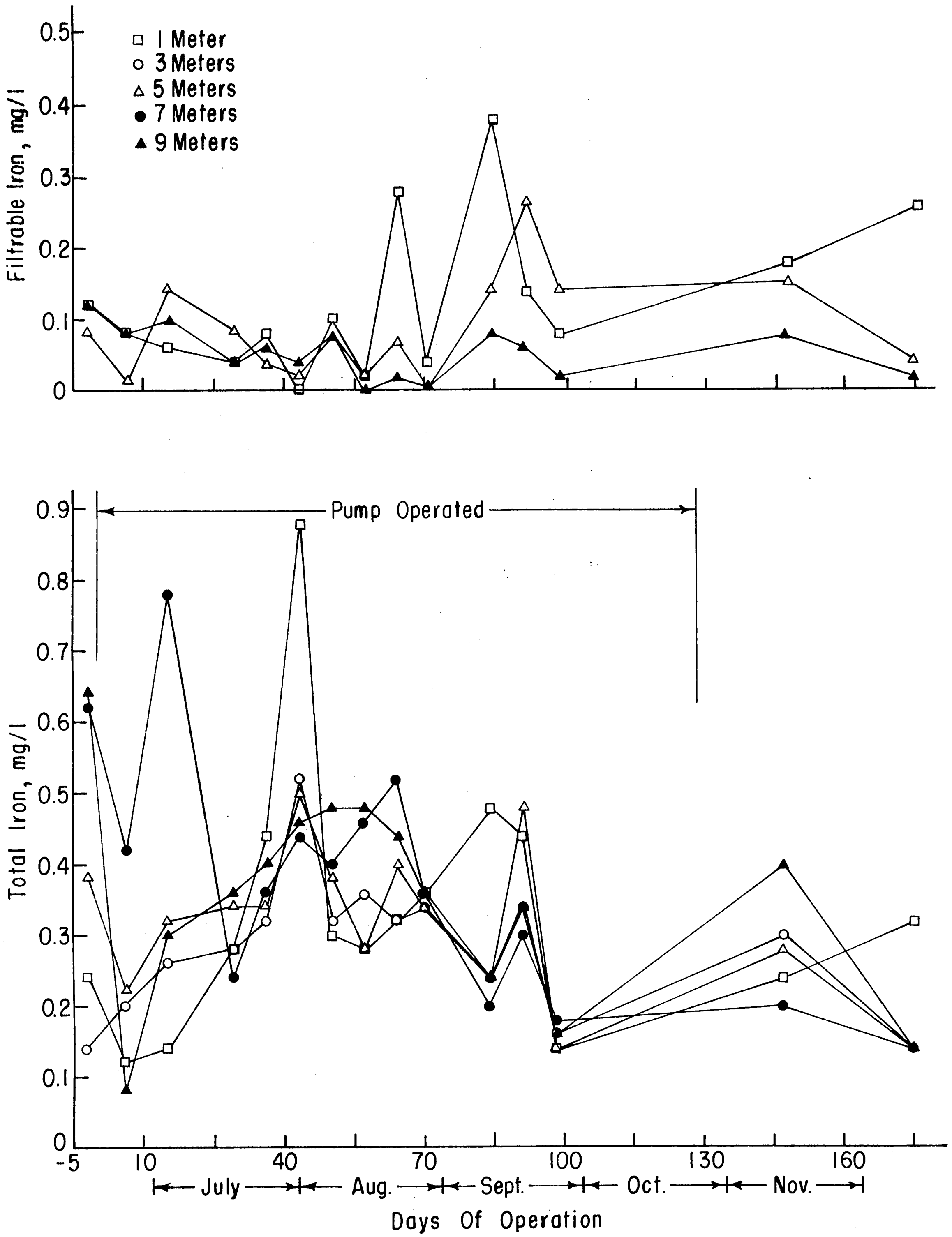


Figure 44. Total Iron and Filtrable Iron Versus Time

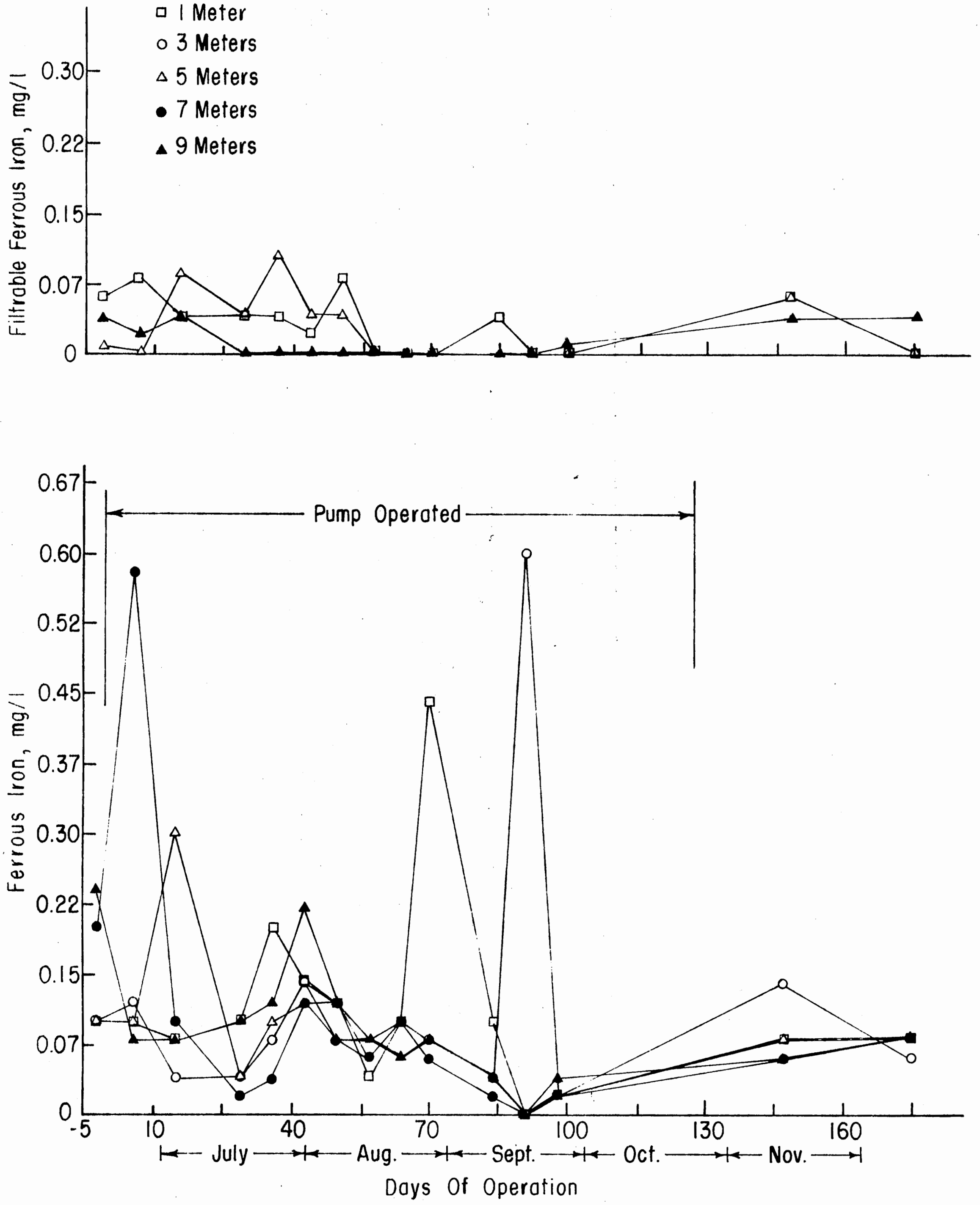


Figure 45. Ferrous Iron and Filtrable Ferrous Iron Versus Time

can reduce ferric hydroxide (13).

These conditions were probably the cause of the sharp increases at seven meters shortly after mixing was begun. However, these conditions were not present during the sharp increases, in the upper waters, in August and September indicating possible contamination or experimental error for these samples.

Filtrable ferrous iron showed little change due to mixing with values always below 0.1 mg/l.

Selected profiles of total iron, filtrable iron, ferrous iron, and filtrable ferrous iron are shown in Figures 65, 66, 67, and 68, respectively.

Total manganese was highly stratified before mixing (Figure 46). At nine meters manganese was above 4.0 mg/l, above 2.0 mg/l at seven meters, and below 0.3 mg/l above five meters. Within a week of mixing the seven and nine meter concentrations had been reduced to 0.4 mg/l and readings slightly increased at three and five meters. Manganese concentration then remained relatively constant below 0.5 mg/l until the fall turnover when it fell to 0.2 mg/l.

Selected profiles of manganese are shown in Figure 69.

Analysis of Pump

Pump Operation

The pump was put into operation at 10:38 a.m. on June 19, 1975, and operated continuously until October 15 except for minor shutdowns. Thunderstorms moving through the area caused fuses to blow in the electrical circuit resulting in a short shutdown of the pump on

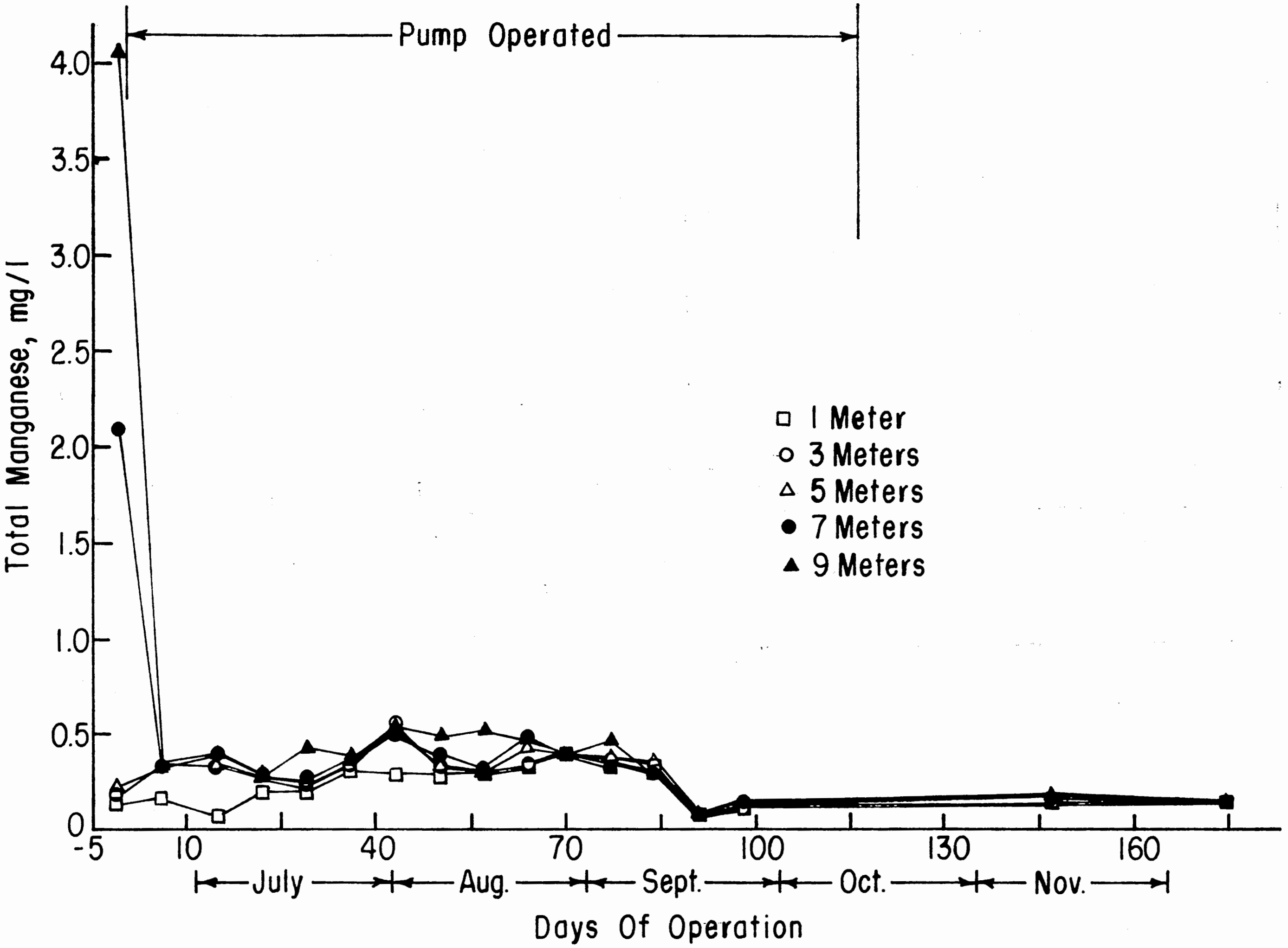


Figure 46. Total Manganese Versus Time

four occasions. The pump was down on two of these occasions from 8:00 p.m. on July 6 to 9:00 a.m. on July 7 and from 5:00 p.m. on July 8 to 9:00 a.m. on July 9. An algae bloom was observed on the morning of July 9. It is not known if these two shutdowns prior to July caused the algae bloom.

Evaluation of Pump Design

Prony brake tests (Figure 47) were run on the drive system to determine the power requirement and the RPM of the propeller when operating in water. Power input to the electric motor when operating the propeller in the lake was 1.1 kW. Results from the prony brake tests showed at this power setting the propeller shaft power was 0.645 kW and the RPM was 16.8.

Calculated power requirement from Equation (2-6) at 16.8 RPM was 0.586 kW. The actual power requirement was 10 percent higher than calculated. Part of this difference may be explained by the replacement of the propeller shaft ball bearings with sleeve bearings. The manufacturer's stated performance in air was determined with the ball bearings while the performance in water was determined with the sleeve bearings. Sleeve bearings were used to prolong bearing life under the submerged conditions.

Calculated flow rate from Equation (2-4) at 16.8 RPM was 1.58 m^3/sec. This required an average velocity of 0.805 m/sec through the orifice.

Average velocity profiles taken at four, six, and eight meters below the surface are shown in Figure 48. The propeller was located 1.8 meters below the surface.

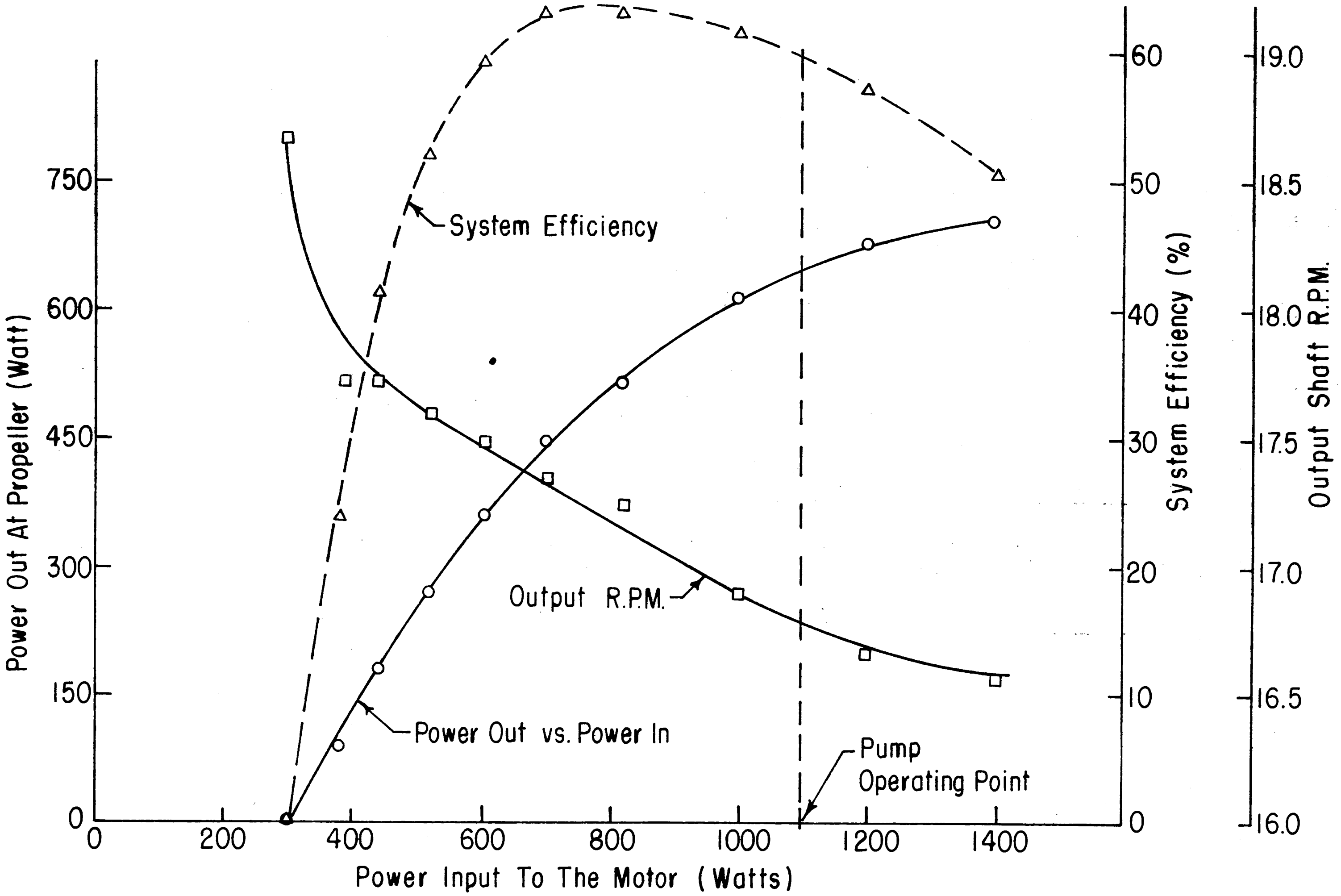


Figure 47. Results of Prony Brake Tests

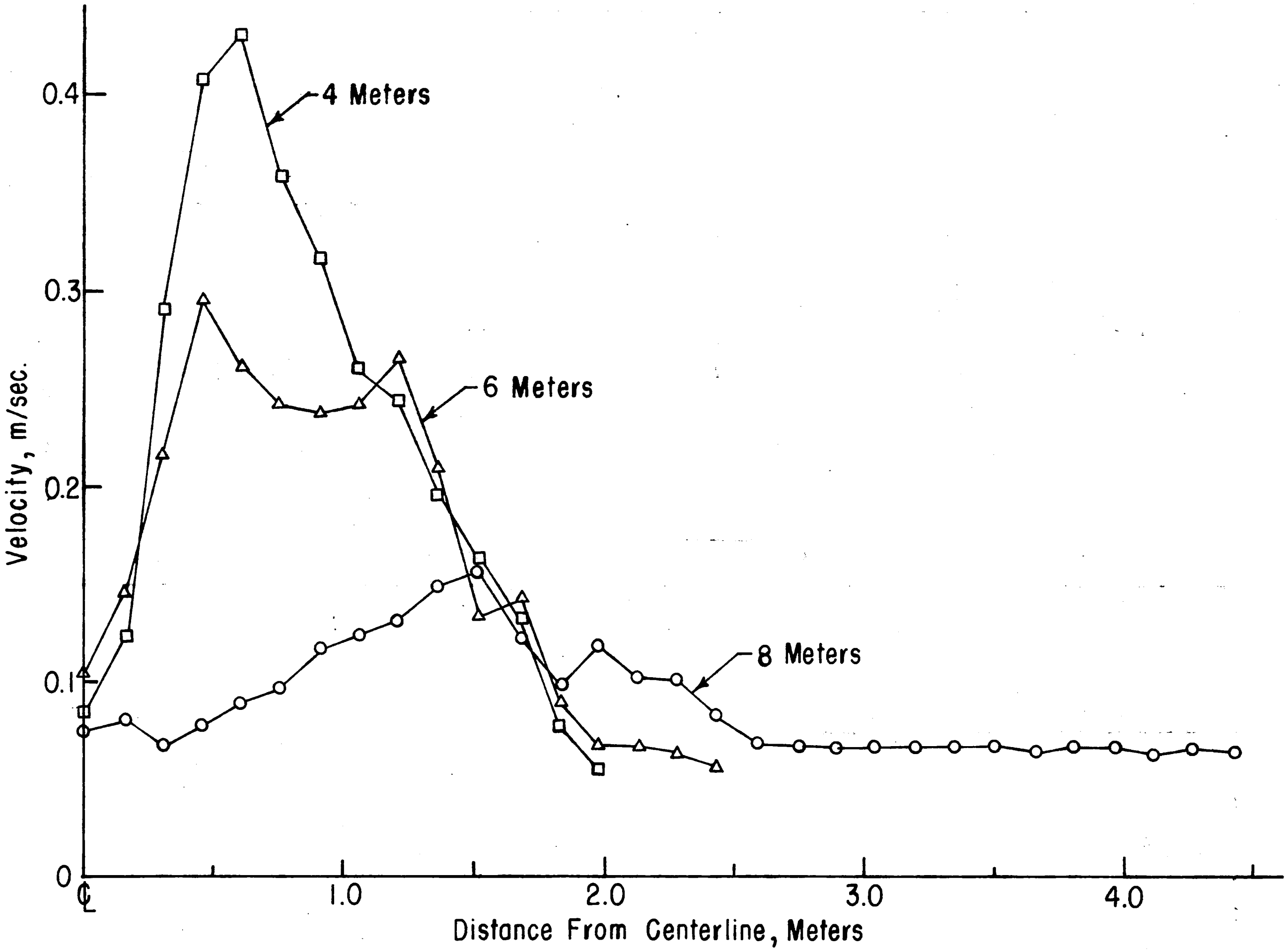


Figure 48. Average Velocity Profiles Versus Distance From Pump Centerline at Depths of Four, Six, and Eight Meters

Total flow rate was calculated from the velocity profiles and the equation for nonuniform flow given by Vennard and Street (40):

$$Q = \int^{A} v \, dA \qquad (5\text{-}1)$$

Calculations showed a flow rate of 2.58, 2.70, and 5.17 m^3/sec at the four, six, and eight meter depths, respectively. The eight meter flow rate was about 3.5 times the calculated pump flow rate. This increase in flow rate was caused by the entrainment of water at the periphery of the discharge cone.

Average fluid velocity over the cross-section of the discharge cone was calculated from the velocity profiles and the equation for nonuniform velocity given by Vennard and Street (40):

$$V = \frac{1}{A}\int^{A} v \, dA \qquad (5\text{-}2)$$

Calculations showed an average velocity of 0.19, 0.14, and 0.08 m/sec at the four, six, and eight meter depths, respectively. Enough energy was added to the fluid to allow complete penetration of the reservoir's depth.

A momentum flux (μ) balance and β (momentum correction for nonuniform flow) values were calculated to try to predict the actual pumping flow rate. The values were calculated from the velocity profiles and the equations defined by Vennard and Street (40) as:

$$\mu = \rho\int^{A} v^2 \, dA \qquad (5\text{-}3)$$

$$\beta = \frac{1}{V}\frac{\int^{A} v^2 \, dA}{\int^{A} v \, dA} \qquad (5\text{-}4)$$

The momentum flux was 0.664, 0.493, and 0.457 kN with β values of 1.33, 1.345, and 1.085 at four, six, and eight meter depths, respectively. Because of this inconsistency between depths the pump flow rate could not be calculated. Velocity measurements of the highly turbulent and swirling water were the probable cause of this inconsistency. Velocity readings between five minute repetitions varied as much as 500 percent.

The angle of divergence for the discharge cone was determined (Figure 49). At four meters the divergence angle was 21° and at six meters was 27.6°. The eight meter divergence angle was not used since it was located 1.0 to 1.5 meters from the reservoir bottom, thus disturbing the discharge cone.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (41) state the angles of divergence for discharge of air into large open spaces have usually ranged from 20 to 24°.

Effectiveness of Pump

The best way to measure the effectiveness of a destratification device is by its ability to reduce the stability index (SI) and the oxygen distribution index (ODI). Reduction of the SI (a value indicating the lake's resistance to mixing) is determined by calculating the destratification efficiency defined in Equation (2-2).

Changes in SI and ODI are shown in Figure 50. After 24 hours of pumping the SI dropped from 2.73 kW•h to 2.06 kW•h and the pump used 15.4 kW•h of energy. The destratification efficiency was equal to 4.35 percent. After 100 hours, SI dropped to 0.59 kW•h and the pump

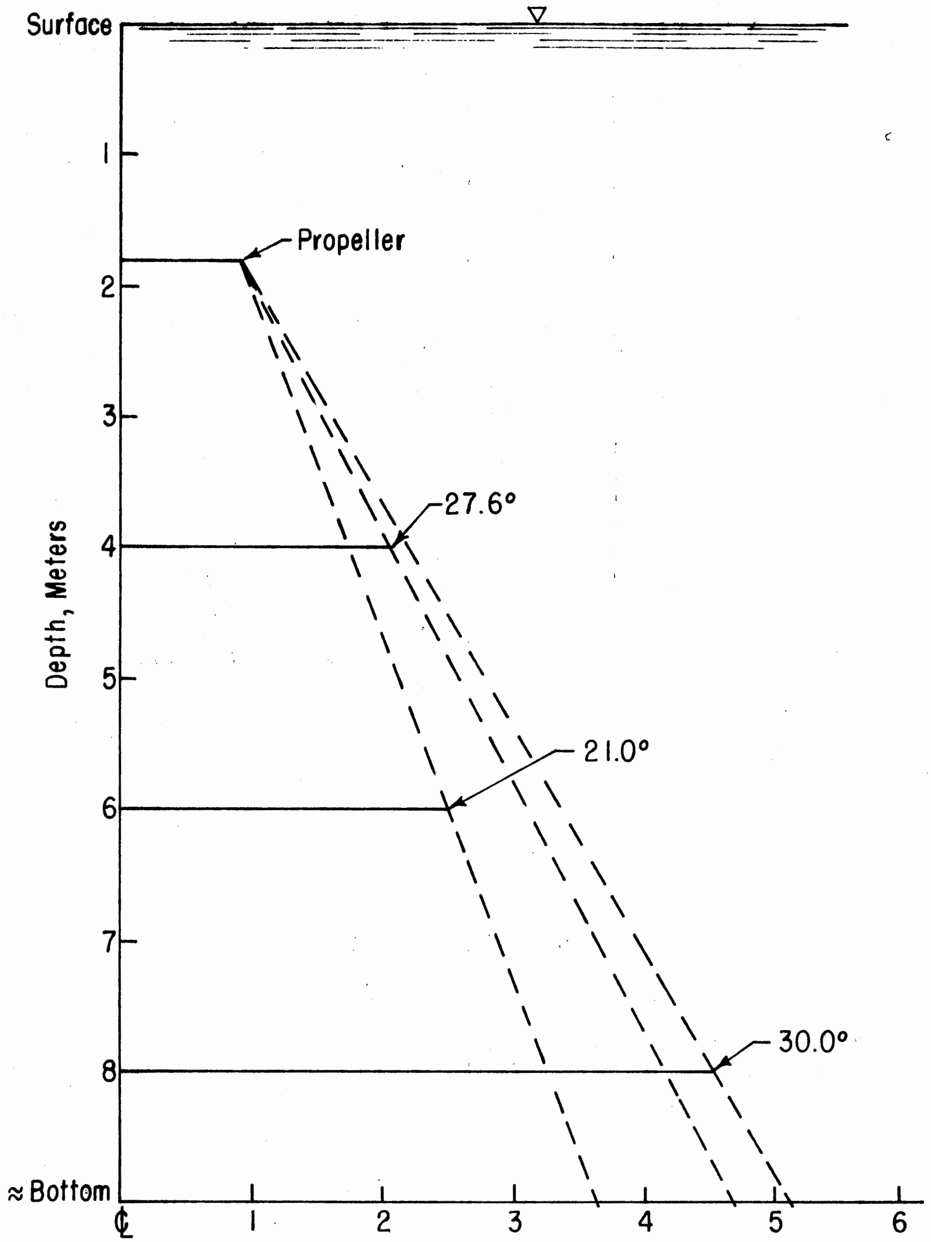


Figure 49. Angle of Divergence at the Four, Six, and Eight Meter Depths

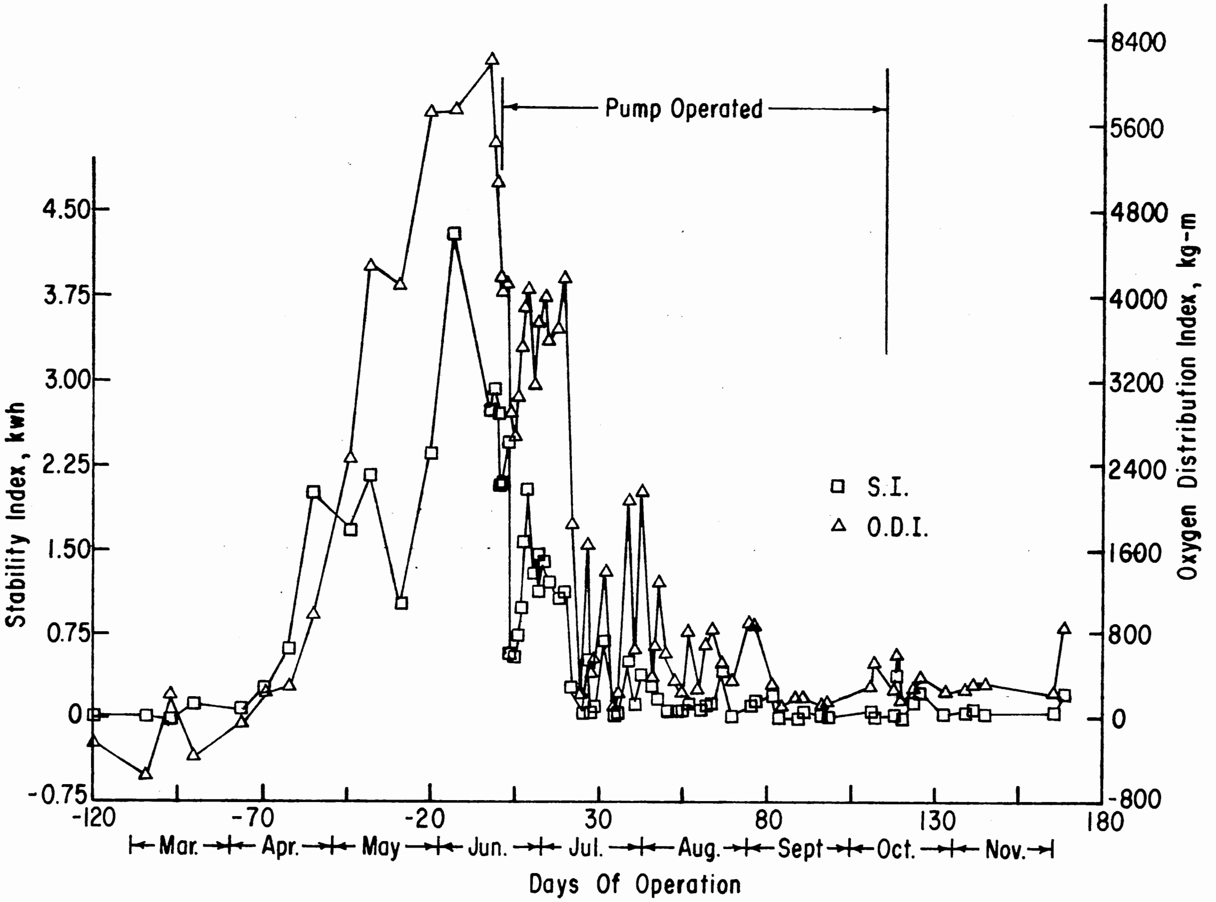


Figure 50. Stability Index and Oxygen Distribution Index Versus Time

had used 65 kW•h of energy. The destratification efficiency was 3.3 percent.

The ODI gives a single value indicating the amount of oxygen stratification in the reservoir. A value of zero indicates a constant oxygen level from the surface to the bottom. This can best be illustrated by plotting several oxygen profiles with their calculated ODI (Figure 51).

The relationship of the ODI to the total oxygen content of the reservoir can be seen in Figure 52. In early March the total oxygen content was 13,800 kilograms and the ODI was zero. As stratification developed, total oxygen decreased as the ODI increased. The day before pumping began total oxygen had decreased to 8,100 kilograms with the ODI increasing to 5060 kg-m. Nearly all of this oxygen was in the top four to five meters of water. Mixing decreased the ODI by distributing the upper water DO throughout the entire reservoir. This resulted in a further decrease of total oxygen because of the high oxygen demand in the lower waters. In early August the total oxygen content began increasing but the ODI continued decreasing. This indicated that DO was being increased at all depths.

After 24 hours of pumping the ODI dropped from 5060 kg-m to 4027 kg-m. After 100 hours it had decreased to 2883 kg-m and after 600 hours dropped to 232 kg-m.

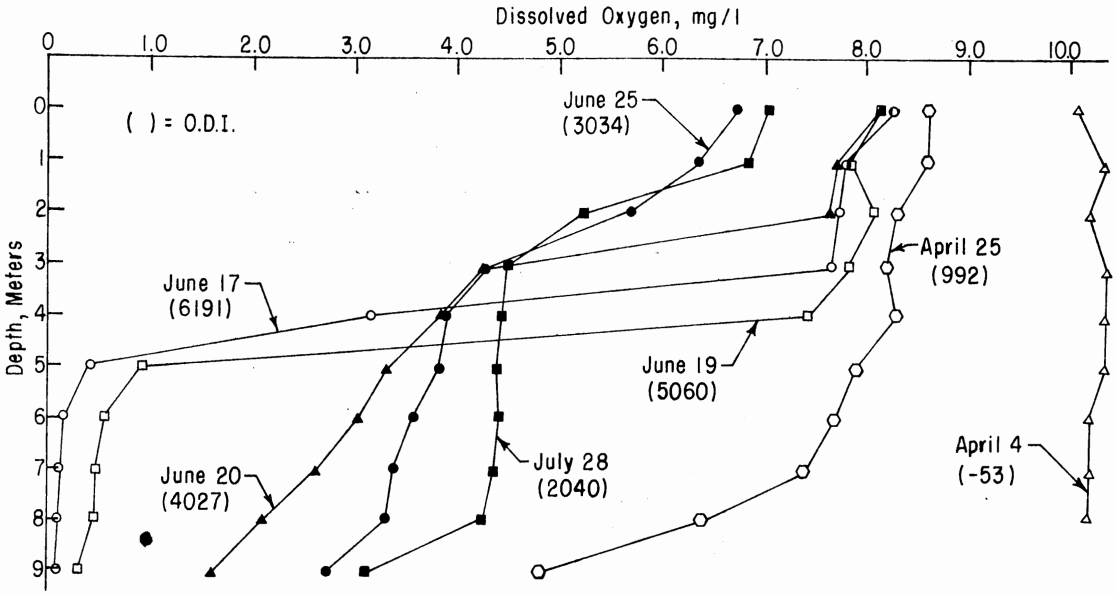


Figure 51. Selected Oxygen Profiles and Their Calculated Oxygen Distribution Index Values

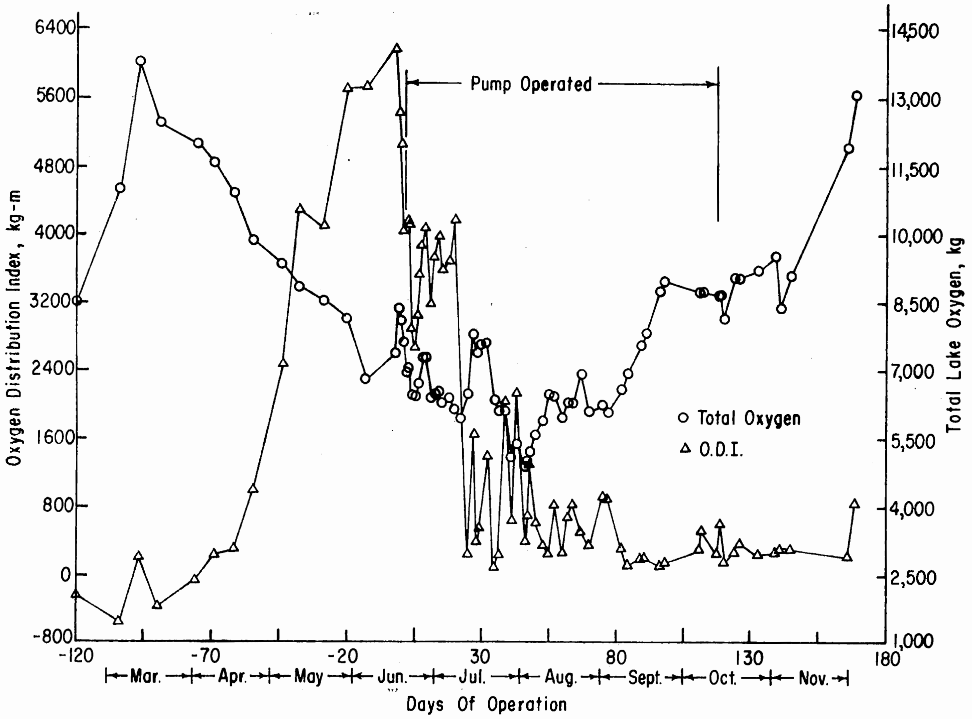


Figure 52. Total Lake Oxygen and Oxygen Distribution Index Versus Time

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

The objectives of this study were to: (1) design and construct a prototype, low-energy, axial down flow propeller pump for use as a destratification device, (2) evaluate the performance of the pump when moving water under a low head, and (3) determine the effect of the pump's operation on the water quality parameters of a stratified reservoir.

A prototype propeller pump was designed using the fan laws and the manufacturer's stated performance in air. The pump was constructed at the Agricultural Engineering Laboratory and transported to Ham's Lake for installation and operation. The pump was started on the morning of June 19 and operated continuously until October 15.

Water quality parameters observed were: temperature, DO, pH, specific conductance, clarity, alkalinity, BOD, COD, iron, manganese, turbidity, solids, and CO_2.

Measurements were taken of the pump power input and shaft RPM. Velocity profiles were taken at four, six, and eight meter depths below the surface.

Conclusions

1. Thermal destratification was achieved by warming the bottom water to the surface water temperature.
2. Four days of pumping were required to thermally destratify the reservoir. Destratification efficiency during this period was 3.3 percent.
3. DO was maintained above 2.0 mg/l in the lower waters of the reservoir and above 5.0 mg/l in the surface waters.
4. Overall water quality in the reservoir was improved. Destratification of the water quality parameters monitored was observed.
5. The fan laws provided an effective means of predicting the performance in water from the available data in air.
6. The angle of divergence for the discharge cone was between 21° and 28°.
7. Considerable amounts of water were entrained at the periphery of the discharge cone.
8. The prototype pump proved to be a simple, economical, and effective destratification device.

Recommendations for Further Study

1. Operate a small-scale pump on a pond or lagoon to determine the proper pumping conditions needed to fit the pump design to a given reservoir.

2. Operate the down flow propeller pump over the outlet structure of a reservoir to determine if downstream water releases can be improved.
3. Sequentially operate the pump to determine if destratification can be achieved without continuously operating the pump.
4. Operate the pump on a fish farm to determine if fish growth can be improved.
5. A further study of the discharge cone behavior is needed to aid in the design of the down flow pump.

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APPENDIXES

APPENDIX A

SOLIDS TEST PROCEDURE

TABLE I

SOLIDS TEST PROCEDURE

(1) Evaporate 100 milliliters of sample in an ignited (600 °C) and tared evaporating dish to constant weight at 103 °C, cool in a desiccator and weigh. This weight, subtracted from the tared weight, is the total solids in the sample.

(2) Take the evaporating dish from Step (1) after it is weighed and ignite at 600 °C in an electric muffle furnace for 15 minutes. Remove from the furnace and allow to cool partially in the air, and then place in a desiccator for 30 minutes. Weigh the evaporating dish. The difference between this weight and the weight in Step (1) is total volatile solids.

(3) Make an asbestos cream by adding 10 grams of acid washed, medium fiber asbestos to one liter of distilled water. Take a Gooch crucible and fill with the asbestos cream. Let stand for one to two minutes and then apply suction. After all the water has been drawn through the mat, the crucible is filled with distilled water which is likewise drawn through. This mat is washed twice with distilled water. The crucible is then transferred to a muffle furnace and ignited at 600 °C for 15 to 20 minutes. Remove from the furnace and after partially cooling in the air, place in a desiccator for 30 minutes and weigh.

(4) Take the weighed crucible from Step (3) and filter

TABLE I (Continued)

250 milliliters of a well mixed sample through the Gooch crucible using the same suction as in Step (3). Place the crucible in an oven and dry for one hour at 103 °C and allow to cool in a desiccator before weighing. The difference in this weight and the weight of the crucible before filtration is the total suspended solids.

(5) Take the crucible in Step (4) after weighing and ignite in a muffle furnace at 600 °C for 20 minutes. Allow to partially cool in the air, and place in a desiccator for 30 minutes for complete cooling. Weigh the crucible. The difference in the weight of the crucible after ignition and the weight before ignition is the suspended volatile solids.

(6) To get the volatile solids in solution, subtract the suspended volatile solids in Step (5) from the total volatile solids obtained in Step (2).

APPENDIX B

COMPUTER PROGRAM FOR CALCULATION OF STABILITY INDEX AND OXYGEN DISTRIBUTION INDEX

TABLE II

COMPUTER PROGRAM TO CALCULATE STABILITY INDEX AND OXYGEN DISTRIBUTION INDEX

```
C     THIS PROGRAM CALCULATES STABILITY INDEX, OXYGEN DISTRIBUTION INDEX
C     AND OTHER LAKE PARAMETERS FOR HAMS LAKE
C     THIS PROGRAM CAN BE USED FOR ANY LAKE BY OBTAINING AN AREA VERSUS
C     DEPTH EQUATION FOR THE PROPOSED LAKE
      DOUBLE PRECISION RSL,RMIX,R,RR,RXM,RRXM,DEN,AREA,VTOT,VTT,VOX,
     *TMASS,TT,OX,SMASS,SI,SIKWH
C     VARIABLES ARE DIMENSIONED ONE MORE THAN THE DEPTH IN METERS
      DIMENSION T(10,10),OD(10,10),SUMT(10),SUMO(10),TAVE(10),OAVE(10)
     $,DATE(5),TIME(3)
  510 WRITE(6,500)
  500 FORMAT(1H1)
      KT=0
      WRITE(6,201)
      WRITE(6,202)
      WRITE(6,203)
      WRITE(6,204)
  201 FORMAT(26X,'SURFACE',5X,'CENTROID',5X,'TOTAL',6X,'SURFACE',5X,'AVE
     ?RAGE',5X,'AVERAGE',6X,'TOTAL',5X,'STABILITY',5X,'OXYGEN')
  202 FORMAT(4X,'DATE',8X,'TIME',5X,'ELEVATION',4X,'ELEVATION',4X,'VOLUM
     ?E',7X,'AREA',5X,'TEMPERATURE',4X,'D.O.',7X,'OXYGEN',6X,'INDEX',4X,
     ?'DISTRIBUTION')
  203 FORMAT(14X,'(MEDIAN)',4X,'(METERS)',4X,'(METERS)',5X,'(HA-M)',4X,'
     ?(HECTARES)',3X,'(DEG. C)',5X,'(MG/L)',7X,'(KG)',7X,'(KWH)',7X,' IN
     ?DEX ')
  204 FORMAT(123X,'(KG-M)')
      WRITE(6,600)
  600 FORMAT(/)
C     A HEADER CARD IS USED FOR EACH SET OF DATA
C     N IS THE NUMBER OF SAMPLING STATIONS
C     ELEV = STAFF GAGE READING IN FEET
C     TIME IS THE MEDIAN TIME OF DATA COLLECTION
   90 READ(5,16) N,(DATE(I),I=1,5),ELEV,(TIME(I),I=1,2)
   16 FORMAT(I2,4X,5A2,F10.0,13X,2A4)
      IF(N.EQ.99) GO TO 99
C     T IS THE TEMPERATURE AND OD IS THE DISSOLVED OXYGEN
C     I IS THE (DEPTH MINUS ONE) IN METERS   J = STATION NUMBER
      READ(5,15)((T(I,J),OD(I,J),I=1,10),J=1,N)
   15 FORMAT(20F4.1)
C     THIS DO LOOP CALCULATES THE AVERAGE TEMPERATURE AND DISSOLVED
C     OXYGEN FOR EACH METER OF DEPTH
      DO 31 I=1,10
      SUMT(I)=0.
      SUMO(I)=0.
      NN=0
      DO 30 J=1,N
      IF(T(I,J).EQ.0.) GO TO 30
      SUMT(I)=SUMT(I)+T(I,J)
      SUMO(I)=SUMO(I)+OD(I,J)
      NN=NN+1
   30 CONTINUE
C     TAVE=AVERAGE TEMP. FOR EACH METER DEPTH
C     OAVE=AVERAGE OXYGEN FOR EACH METER DEPTH
      TAVE(I) = SUMT(I)/NN
      OAVE(I) = SUMO(I)/NN
   31 CONTINUE
      VTOT=0.
      VTT=0.
      VOX=0.
```

TABLE II (Continued)

```
0037              RXM=0.
0038              RRXM=0
0039              TMASS=0.
0040              OXV=0.0
0041              K=1
0042              I=0
0043              Y=0.0
0044              Z=3.28084
            C     THIS NEXT CARD IS SET AT THE MAXIMUM DEPTH AT WHICH DATA WAS
            C     COLLECTED
0045          100 IF(I.EQ.9) GO TO 50
            C     SLICES ARE CONSIDERED AS FRUSTUM OF PYRAMID (WITH BASE OF ANY SHAPE)
            C     TT=AVERAGE TEMP OF 1 METER SLICE OF STRATIFIED LAKE WEIGHTED BY AREA
0046              TT=((AREA(ELEV-Y)*TAVE(K))+((AREA(ELEV-Y)*AREA(ELEV-Z)*TAVE(K)*TAV
                 ?E(K+1))**.5)+(AREA(ELEV-Z)*TAVE(K+1)))/(AREA(ELEV-Y)+((AREA(ELEV-Y
                 ?)*AREA(ELEV-Z))**.5)+AREA(ELEV-Z))
            C     V=VOLUME OF 1 METER SLICE
0047              V=(AREA(ELEV-Y)+(AREA(ELEV-Y)*AREA(ELEV-Z))**.5+AREA(ELEV-Z))/3.0
            C     VTOT=TOTAL VOLUME OF LAKE
0048              VTOT=VTOT+V
            C     VTT=SUM OF (SLICE VOLUME * AVERAGE TEMP OF SLICE) FOR STRATIFIED LAKE
0049              VTT=VTT+(V*TT)
            C     OX=AVERAGE OXYGEN OF 1 METER SLICE OF STRATIFIED LAKE WEIGHTED BY AREA
0050              IF(OAVE(K).EQ.0.0) GO TO 40
0051              IF(OAVE(K+1).EQ.0.0) GO TO 45
0052              OX=((AREA(ELEV-Y)*OAVE(K))+((AREA(ELEV-Y)*AREA(ELEV-Z)*OAVE(K)*OAV
                 ?E(K+1))**.5)+(AREA(ELEV-Z)*OAVE(K+1)))/(AREA(ELEV-Y)+((AREA(ELEV-Y
                 ?)*AREA(ELEV-Z))**.5)+AREA(ELEV-Z))
0053              GO TO 41
0054           40 OX=0.0
0055              GO TO 41
0056           45 OX=(AREA(ELEV-Y)*OAVE(K))/(AREA(ELEV-Y)+((AREA(ELEV-Y)*AREA(ELEV-Z
                 ?))**.5)+AREA(ELEV-Z))
            C     VOX=SUM OF (SLICE VOLUME * AVERAGE OXYGEN OF SLICE ) FOR STRATIFIED LAKE
0057           41 VOX=VOX+(OX*V)
0058              IF(OAVE(K).EQ.0.0) GO TO 60
0059              IF(OAVE(K+1).EQ.0.0) GO TO 53
            C     OXSL - CALCULATES OXYGEN CENTROID FOR 1 METER SLICE OF STRATIFIED LAKE
0060              OXSL=.25*((AREA(ELEV-Y)*OAVE(K)+2*((AREA(ELEV-Y)*AREA(ELEV-Z)*OAVE
                 ?(K)*OAVE(K+1))**.5)+3*AREA(ELEV-Z)*OAVE(K+1))/(AREA(ELEV-Y)*OAVE(K
                 ?)+(AREA(ELEV-Y)*AREA(ELEV-Z)*OAVE(K)*OAVE(K+1))**.5+AREA(ELEV-Z)*O
                 ?AVE(K+1)))
0061              GO TO 54
0062           53 OXSL=.25
            C     SVXO - CALCULATES TOTAL OXYGEN FOR 1 METER SLICE OF STRATIFIED LAKE
0063           54 SVXO=(OX*V*10.0)
            C     OXV - SUM OF (SLICE OXYGEN * DISTANCE FROM SURFACE TO SLICE OXYGEN
            C     CENTROID)
0064              OXV=OXV + (SVXO*(I+OXSL))
0065           60 CONTINUE
            C     RSL = CENTROID OF 1 METER SLICE OF STRATIFIED LAKE
0066              RSL=.25*((AREA(ELEV-Y)*DEN(TAVE(K))+2*((AREA(ELEV-Y)*AREA(ELEV-Z)*
                 ?DEN(TAVE(K))*DEN(TAVE(K+1)))**.5)+3*AREA(ELEV-Z)*DEN(TAVE(K+1)))/(
                 ?AREA(ELEV-Y)*DEN(TAVE(K))+(AREA(ELEV-Y)*AREA(ELEV-Z)*DEN(TAVE(K))*
                 ?DEN(TAVE(K+1)))**.5+AREA(ELEV-Z)*DEN(TAVE(K+1))))
            C     SMASS=MASS OF 1 METER SLICE OF STRATIFIED LAKE
0067              SMASS=(AREA(ELEV-Y)*DEN(TAVE(K))+(AREA(ELEV-Y)*AREA(ELEV-Z)*DEN(TA
                 ?VE(K))*DEN(TAVE(K+1)))**.5+AREA(ELEV-Z)*DEN(TAVE(K+1)))/3.0
```

TABLE II (Continued)

```
C     RXM=SUM OF (SLICE MASS * DISTANCE FROM SURFACE TO SLICE CENTROID)
C     FOR STRATIFIED LAKE
      RXM=RXM+(SMASS*(I+RSL))
C     TMASS=TOTAL MASS OF STRATIFIED LAKE
      TMASS=TMASS+SMASS
C     RMIX=CENTROID OF 1 METER SLICE OF DESTRATIFIED LAKE
      RMIX=.25*((AREA(ELEV-Y)+2*((AREA(ELEV-Y)*AREA(ELEV-Z))**.5)+3*AREA
     ?(ELEV-Z))/(AREA(ELEV-Y)+(AREA(ELEV-Y)*AREA(ELEV-Z))**.5+AREA(ELEV-
     ?Z)))
C     RRXM=SUM OF (SLICE VOLUME * DISTANCE FROM SURFACE TO SLICE CENTROID)
C     FOR DESTRATIFIED LAKE
      RRXM=RRXM+(V*(I+RMIX))
      I=I+1
      K=K+1
      Y=Y+3.28084
      Z=Z+3.28084
      GO TO 100
   50 CONTINUE
C     THESE NEXT STATEMENTS CALCULATE VOLUME,CENTROID,AND MASS OF THE
C     WATER BELOW 9 METERS
C     THESE ASSUME THE TEMPERATURE AND OXYGEN BELOW 9 METERS IS THE SAME
C     AS THE 9 METER READINGS
      V=(((ELEV-Y)+23.3)/3.0)*AREA(ELEV-Y)*.3048
      VTOT=VTOT+V
      VTT=VTT+(V*TAVE(K))
      VOX=VOX+(V*OAVE(K))
      RSL=(((ELEV-Y)+23.3)*.3048)/4.0
      OXSL=RSL
      SVXO=(V*OAVE(9)*10.0)
      OXV=OXV + (SVXO*(I+OXSL))
      SMASS=(((ELEV-Y)+23.3)/3.0)*AREA(ELEV-Y)*DEN(TAVE(K))*.3048
      RXM=RXM+(SMASS*(I+RSL))
      TMASS=TMASS+SMASS
      RRXM=RRXM+(V*(I+RSL))
C     TLAKE=AVERAGE TEMPERATURE OF THE STRATIFIED LAKE
C     OXKG=TOTAL DISSOLVED OXYGEN OF STRATIFIED LAKE
C     AVDO=AVERAGE DISSOLVED OXYGEN OF STRATIFIED LAKE (MG/LITER)
C     R=DISTANCE FROM SURFACE TO CENTER OF MASS OF STRATIFIED LAKE
C     RR=DISTANCE FROM SURFACE TO CENTER OF MASS OF DESTRATIFIED LAKE
      TLAKE=VTT/VTOT
      OXKG=VOX*10.0
      AVDO=VOX/VTOT
      R=RXM/TMASS
      RR=RRXM/VTOT
C     RO = DISTANCE FROM SURFACE TO OXYGEN CENTROID OF STRATIFIED LAKE
      RO=OXV/OXKG
C     ODI = OXYGEN DISTRIBUTION INDEX (KG-M)
      ODI=(RR-RO)*OXKG
C     SI = STABILITY INDEX (KG/M)
      SI=(R-RR)*TMASS*1.0E7
C     SIKWH = STABILITY INDEX (KWH)
      SIKWH=SI*2.72407E-6
C     ALT = ELEVATION OF LAKE SURFACE (METERS)
      ALT=928.9 + ELEV
      ALT=ALT*0.3048
C     CENT = ELEVATION OF LAKE CENTROID (METERS)
      CENT=ALT-R
      VOLUM=VTOT
```

TABLE II (Continued)

```
      AREAL=AREA(ELEV)
      WRITE(6,200)(DATE(I),I=1,5),(TIME(I),I=1,2),ALT,CENT,VOLUM,AREAL,T
     ?LAKE,AVDO,OXKG,SIKWH,ODI
  200 FORMAT(1X,5A2,3X,2A4,3X,F8.2,4X,F8.2,5X,F7.1,5X,F6.1,6X,F6.1,6X,F6
     ?.1,5X,F8.0,4X,F8.4,4X,F8.2)
      KT=KT+1
      IF(KT.EQ.45) GO TO 510
      GO TO 90
   99 WRITE(6,500)
      STOP
      END
```

```
C     THIS FUNCTION CALCULATES AREA IN HECTARES AS A FUNCTION OF DEPTH
      FUNCTION AREA(ELEV)
      DOUBLE PRECISION AREA
      D= ELEV + 23.3
      AREA=(1.00277*D) -(0.11605*D**2)+(0.0065715*D**3)-(0.00005537*D**4
     $)
      AREA=AREA*0.40469
      RETURN
      END
```

```
C     THIS FUNCTION CALCULATES THE DENSITY OF WATER AS A FUNCTION OF
C     TEMPERATURE
      FUNCTION DEN(T)
      DOUBLE PRECISION DEN
      DEN=0.999868508517322 D0 +(0.671760015421274 D-4*T)-(0.89302500826
     $9373 D-5*T**2)+(0.861137053280717 D-7*T**3)-(0.616235641457997 D-9
     $*T**4)
      RETURN
      END
```

TABLE III
STABILITY INDEX, OXYGEN DISTRIBUTION INDEX, AND OTHER LAKE PARAMETERS

DATE	TIME (MEDIAN)	SURFACE ELEVATION (METERS)	CENTROID ELEVATION (METERS)	TOTAL VOLUME (HA-M)	SURFACE AREA (HECTARES)	AVERAGE TEMPERATURE (DEG. C)	AVERAGE D.O. (MG/L)	TOTAL OXYGEN (KG)	STABILITY INDEX (KWH)	OXYGEN DISTRIBUTION INDEX (KG-M)
FEB 19 75	3:30 PM	286.88	284.52	110.1	38.9	4.8	7.7	8499.	0.0081	-238.44
MAR 7 75	3:30 PM	287.06	284.68	117.2	40.8	5.8	9.4	11016.	0.0114	-568.13
MAR 14 75	3:30 PM	287.37	284.95	130.0	44.1	3.6	10.6	13775.	-0.0153	212.10
MAR 21 75	3:30 PM	287.15	284.76	121.0	41.8	9.4	10.3	12415.	0.1186	-386.42
APR 4 75	3:15 PM	287.09	284.71	118.5	41.1	9.3	10.1	12010.	0.0658	-53.17
APR 11 75	3:00 PM	287.11	284.72	119.1	41.3	11.4	9.7	11571.	0.2566	239.72
APR 18 75	3:00 PM	287.11	284.72	119.1	41.3	18.1	9.2	10898.	0.6327	292.73
APR 25 75	3:00 PM	287.11	284.72	119.1	41.3	22.1	8.3	9849.	2.0135	992.03
MAY 6 75	3:00 PM	287.11	284.72	119.1	41.3	20.8	7.8	9333.	1.6742	2462.68
MAY 12 75	3:00 PM	287.09	284.71	118.5	41.1	21.3	7.5	8845.	2.1678	4299.31
MAY 21 75	11:00 AM	287.56	285.11	138.8	46.3	21.9	6.1	8532.	1.0248	4085.12
MAY 30 75	10:30 AM	287.70	285.23	145.2	47.8	21.6	5.6	8127.	2.3469	5701.51
JUNE 6 75	10:20 AM	287.03	284.65	116.0	40.5	24.2	5.8	6776.	4.2982	5721.78
JUNE 17 75	11:45 AM	287.11	284.72	119.1	41.3	23.7	6.2	7378.	2.7260	6191.20
JUNE 18 75	4:00 PM	287.09	284.71	118.5	41.1	24.7	7.1	8386.	2.9291	5426.23
JUNE 19 75	10:15 AM	287.09	284.71	118.5	41.1	24.5	6.8	8097.	2.7255	5060.32
JUNE 19 75	12:05 PM	287.09	284.71	118.5	41.1	24.2	6.4	7593.	2.8871	5537.86
JUNE 19 75	1:05 PM	287.09	284.71	118.5	41.1	24.9	7.0	8248.	2.8906	4797.15
JUNE 19 75	3:35 PM	287.09	284.71	118.5	41.1	25.2	6.8	8031.	3.2243	5387.50
JUNE 19 75	6:30 PM	287.09	284.71	118.5	41.1	25.4	7.0	8260.	3.3469	5199.18
JUNE 19 75	9:45 PM	287.09	284.71	118.5	41.1	25.2	6.5	7703.	3.3331	5474.44
JUNE 20 75	10:00 AM	287.09	284.71	118.5	41.1	24.9	6.4	7618.	2.0645	4027.13
JUNE 20 75	12:10 PM	287.09	284.71	118.5	41.1	25.0	6.6	7845.	2.9864	5192.36
JUNE 20 75	5:00 PM	287.09	284.71	118.5	41.1	25.7	6.8	8078.	3.0963	4810.88
JUNE 21 75	10:00 AM	287.09	284.71	118.5	41.1	25.2	5.9	6933.	2.0995	4167.47
JUNE 21 75	4:45 PM	287.09	284.71	118.5	41.1	26.2	6.2	7373.	2.8636	4241.93
JUNE 22 75	8:00 PM	287.11	284.72	119.1	41.3	26.1	5.9	7032.	2.4733	4113.21
JUNE 23 75	2:55 PM	287.11	284.72	119.1	41.3	25.0	5.4	6442.	0.5904	2882.91
JUNE 24 75	10:15 AM	287.11	284.72	119.1	41.3	25.1	5.4	6413.	0.5494	2644.62
JUNE 25 75	9:40 AM	287.11	284.72	119.1	41.3	25.5	5.5	6598.	0.7304	3034.24
JUNE 26 75	11:55 AM	287.09	284.71	118.5	41.1	26.1	5.7	6700.	0.9988	3519.70
JUNE 27 75	11:25 AM	287.09	284.71	118.5	41.1	26.6	6.2	7288.	1.5879	3873.05
JUNE 28 75	12:05 PM	287.09	284.71	118.5	41.1	27.3	6.1	7269.	2.0389	4064.22
JUNE 30 75	9:50 AM	287.09	284.71	118.5	41.1	27.4	5.4	6355.	1.3161	3155.60
JULY 1 75	10:00 AM	287.09	284.71	118.5	41.1	27.7	5.4	6400.	1.4622	3726.14
JULY 2 75	10:00 AM	287.06	284.68	117.2	40.8	27.7	5.5	6486.	1.1415	3746.98
JULY 3 75	10:50 AM	287.06	284.68	117.2	40.8	28.2	5.6	6556.	1.4151	3987.66
JULY 4 75	11:20 AM	287.09	284.71	118.5	41.1	28.4	5.3	6271.	1.1953	3557.24
JULY 7 75	10:00 AM	287.03	284.66	116.0	40.5	29.1	5.5	6378.	1.0452	3677.16
JULY 9 75	10:15 AM	287.03	284.66	116.0	40.5	29.5	5.3	6143.	1.1334	4170.77
JULY 11 75	10:30 AM	287.03	284.66	116.0	40.5	29.2	5.1	5940.	0.2846	1843.23
JULY 14 75	10:15 AM	287.00	284.63	114.8	40.2	27.6	5.6	6444.	0.0530	232.54
JULY 16 75	2:00 PM	286.95	284.59	113.0	39.7	28.1	6.9	7769.	0.5314	1641.94
JULY 17 75	9:50 AM	286.95	284.59	113.0	39.7	27.6	6.5	7381.	0.0597	399.44
JULY 18 75	10:20 AM	286.95	284.59	113.0	39.7	27.7	6.7	7574.	0.1034	566.83

TABLE III (Continued)

DATE	TIME (MEDIAN)	SURFACE ELEVATION (METERS)	CENTROID ELEVATION (METERS)	TOTAL VOLUME (HA-M)	SURFACE AREA (HECTARES)	AVERAGE TEMPERATURE (DEG. C)	AVERAGE D.O. (MG/L)	TOTAL OXYGEN (KG)	STABILITY INDEX (KWH)	OXYGEN DISTRIBUTION INDEX (KG-M)
JULY 21 75	10:15 AM	286.92	284.56	111.8	39.4	28.8	6.8	7621.	0.6914	1388.37
JULY 24 75	1:50 PM	286.94	284.58	112.4	39.6	28.7	5.7	6355.	0.0046	67.08
JULY 25 75	9:50 AM	286.94	284.58	112.4	39.6	28.1	5.4	6096.	0.0430	229.39
JULY 28 75	10:05 AM	286.94	284.58	112.4	39.6	28.5	5.4	6088.	0.5190	2039.72
JULY 30 75	10:05 AM	286.94	284.58	112.4	39.6	28.3	4.5	5073.	0.1239	640.23
AUG 1 75	10:15 AM	286.94	284.58	112.4	39.6	28.7	4.8	5415.	0.4003	2135.70
AUG 4 75	10:10 AM	286.94	284.58	112.4	39.6	28.7	4.3	4867.	0.2662	385.21
AUG 5 75	10:55 AM	286.92	284.56	111.8	39.4	28.8	4.5	4999.	0.2864	684.93
AUG 6 75	9:30 AM	286.92	284.56	111.8	39.4	28.8	4.7	5205.	0.1684	1295.75
AUG 8 75	9:40 AM	286.91	284.55	111.2	39.2	28.7	5.0	5588.	0.0724	616.93
AUG 11 75	9:30 AM	286.88	284.52	110.1	38.9	28.8	5.3	5880.	0.0550	346.89
AUG 13 75	9:50 AM	286.86	284.51	109.5	38.8	28.7	5.9	6481.	0.0560	221.39
AUG 15 75	9:35 AM	286.88	284.52	110.1	38.9	28.8	5.8	6421.	0.1124	818.77
AUG 18 75	9:40 AM	286.86	284.51	109.5	38.8	28.4	5.4	5952.	0.0706	246.16
AUG 20 75	9:30 AM	286.86	284.51	109.5	38.8	28.7	5.8	6298.	0.0883	682.96
AUG 22 75	9:45 AM	286.86	284.51	109.5	38.8	29.0	5.7	6282.	0.1191	836.07
AUG 25 75	3:30 PM	286.82	284.47	107.8	38.3	29.2	6.4	6927.	0.4178	502.61
AUG 28 75	9:45 AM	286.79	284.44	106.6	38.0	27.6	5.7	6080.	0.0170	331.28
SEPT 2 75	9:45 AM	286.76	284.42	105.5	37.7	28.3	5.9	6241.	0.1137	908.54
SEPT 4 75	9:25 AM	286.74	284.40	104.9	37.5	28.6	5.8	6081.	0.1629	875.27
SEPT 9 75	9:53 AM	286.69	284.36	103.2	37.1	27.2	6.4	6573.	0.2059	309.53
SEPT 11 75	9:45 AM	286.69	284.36	103.2	37.1	26.8	6.7	6940.	0.0003	107.57
SEPT 16 75	9:25 AM	286.71	284.38	103.8	37.2	21.8	7.3	7545.	-0.0045	207.40
SEPT 18 75	9:45 AM	286.71	284.38	103.8	37.2	21.8	7.5	7828.	0.0650	201.99
SEPT 23 75	9:30 AM	286.68	284.35	102.7	36.9	20.2	8.5	8762.	0.0391	118.19
SEPT 25 75	9:30 AM	286.66	284.34	102.1	36.8	19.5	8.8	8972.	0.0247	143.45
OCT 8 75	10:40 AM	286.57	284.26	98.9	35.9	19.0	8.8	8729.	0.0748	304.83
OCT 9 75	9:00 AM	286.60	284.28	99.9	36.2	19.4	8.8	8829.	0.0107	308.86
OCT 15 75	3:45 PM	286.66	284.34	102.1	36.8	20.7	8.5	8675.	0.0225	247.13
OCT 16 75	2:45 PM	286.66	284.34	102.1	36.8	20.2	8.5	8679.	0.3761	599.40
OCT 17 75	9:50 AM	286.66	284.34	102.1	36.8	19.3	8.0	8134.	0.0002	152.65
OCT 21 75	1:55 PM	286.63	284.31	101.0	36.5	18.7	9.0	9070.	0.1284	273.50
OCT 23 75	2:40 PM	286.63	284.31	101.0	36.5	18.7	8.9	9033.	0.2074	388.44
OCT 30 75	9:40 AM	286.60	284.28	99.9	36.2	15.8	9.2	9207.	0.0295	243.07
NOV 5 75	10:00 AM	286.66	284.34	102.1	36.8	14.1	9.3	9530.	0.0674	265.84
NOV 7 75	10:35 AM	286.60	284.28	99.9	36.2	16.2	8.4	8391.	0.0836	308.68
NOV 11 75	2:15 PM	286.60	284.28	99.9	36.2	15.6	9.1	9116.	0.0357	314.23
DEC 2 75	4:15 PM	286.57	284.26	98.9	35.9	7.4	12.1	11929.	0.0297	218.69
DEC 5 75	10:20 AM	286.57	284.26	98.9	35.9	12.0	13.2	13074.	0.2074	849.45

APPENDIX C

SELECTED PROFILES OF WATER QUALITY PARAMETERS

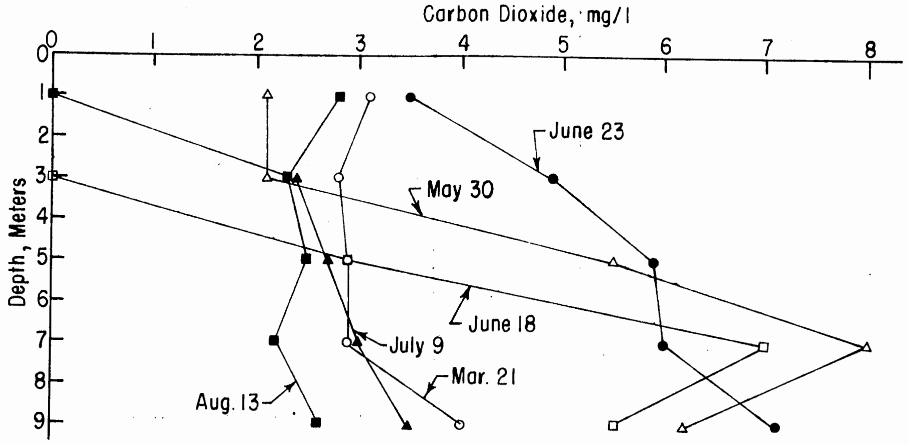

Figure 53. Selected Profiles of Carbon Dioxide

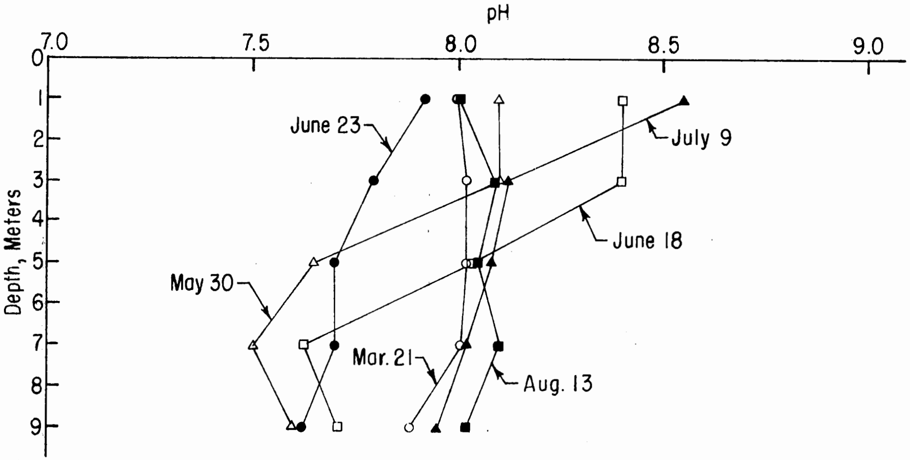

Figure 54. Selected Profiles of pH

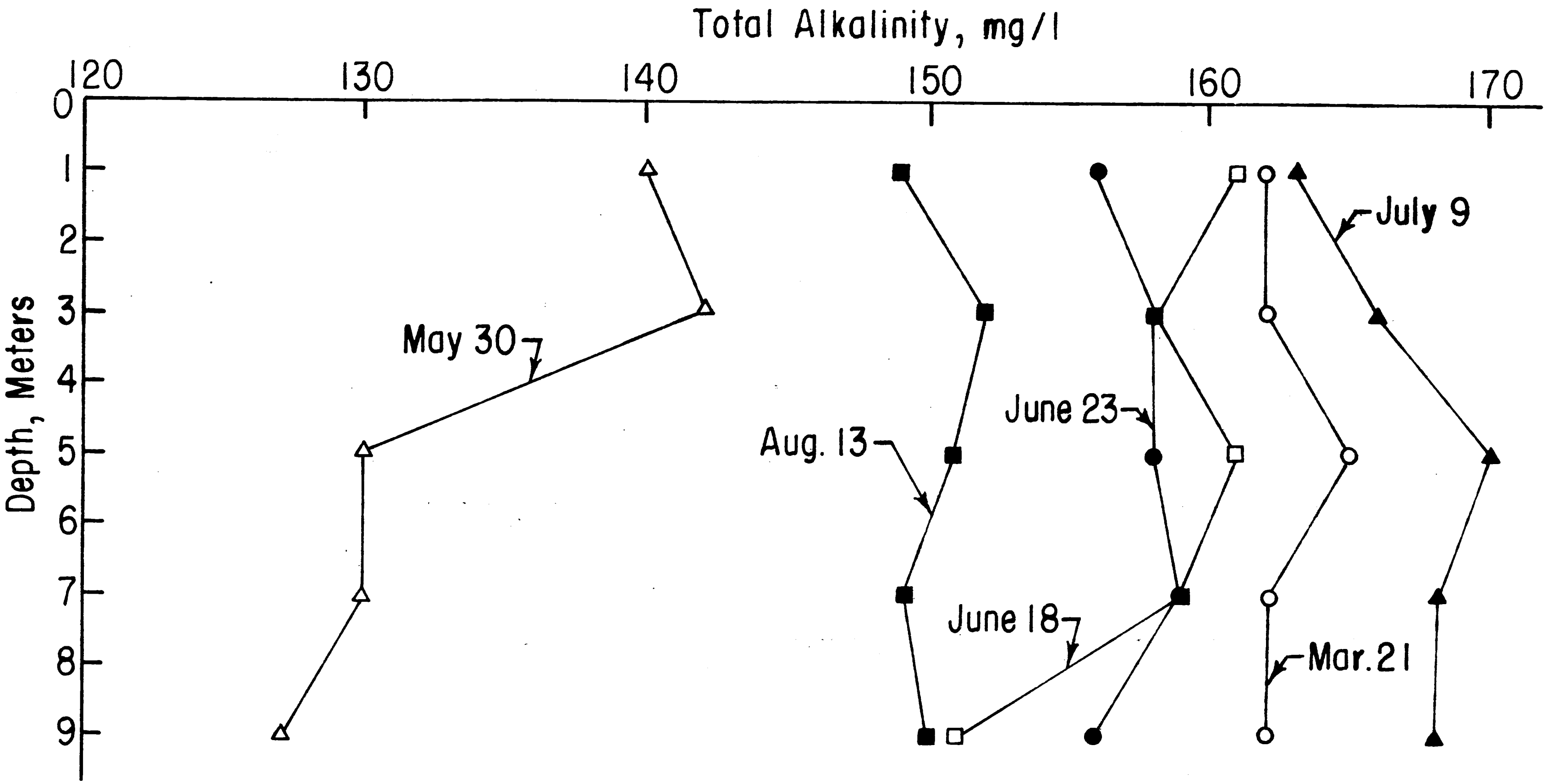

Figure 55. Selected Profiles of Total Alkalinity

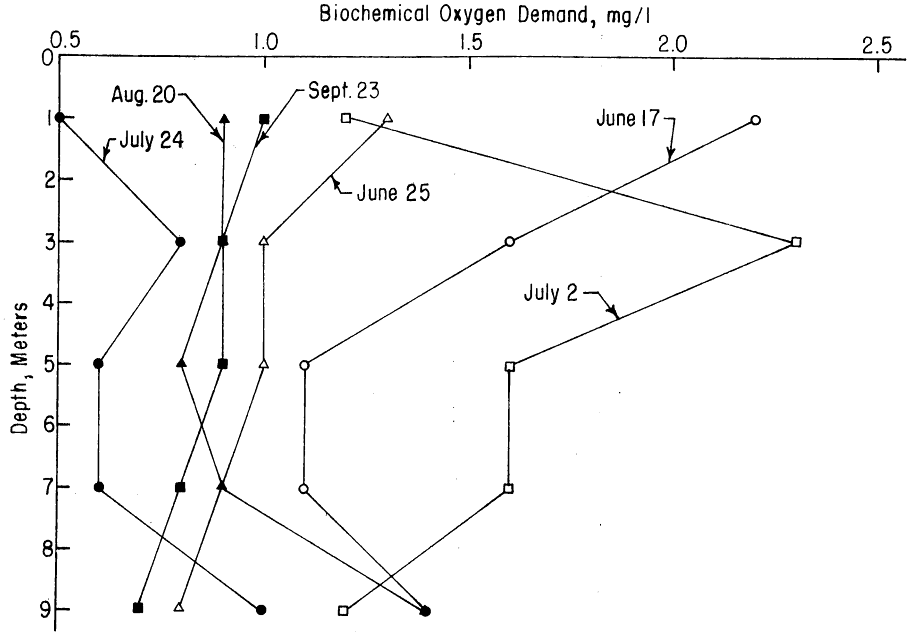

Figure 56. Selected Profiles of Biochemical Oxygen Demand

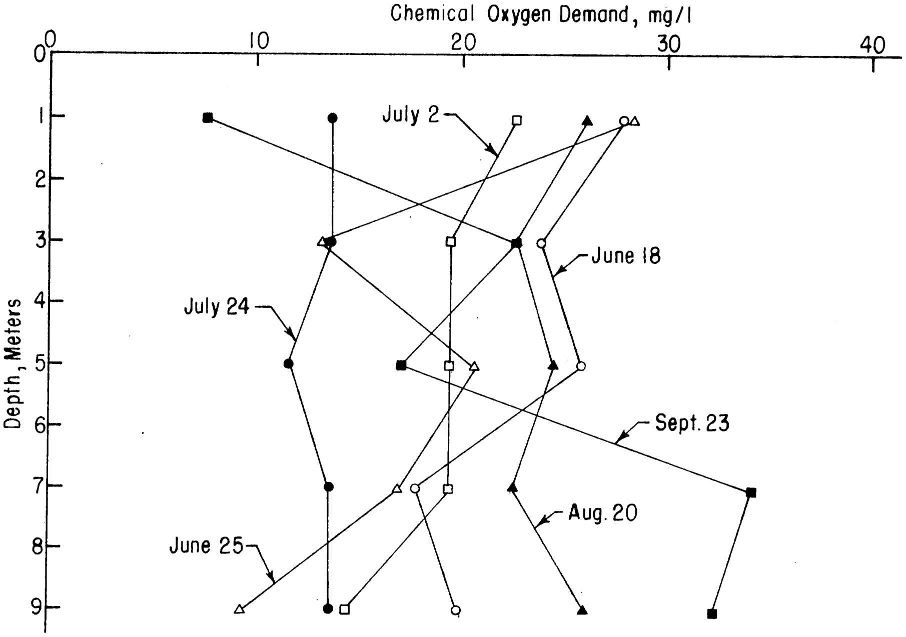

Figure 57. Selected Profiles of Chemical Oxygen Demand

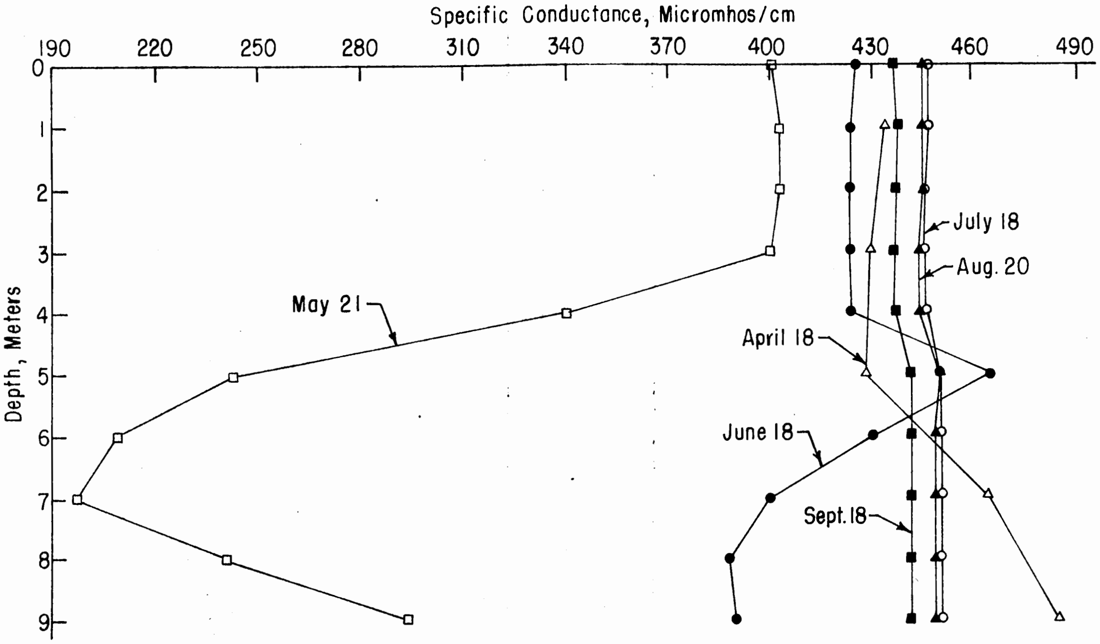

Figure 58. Selected Profiles of Specific Conductance

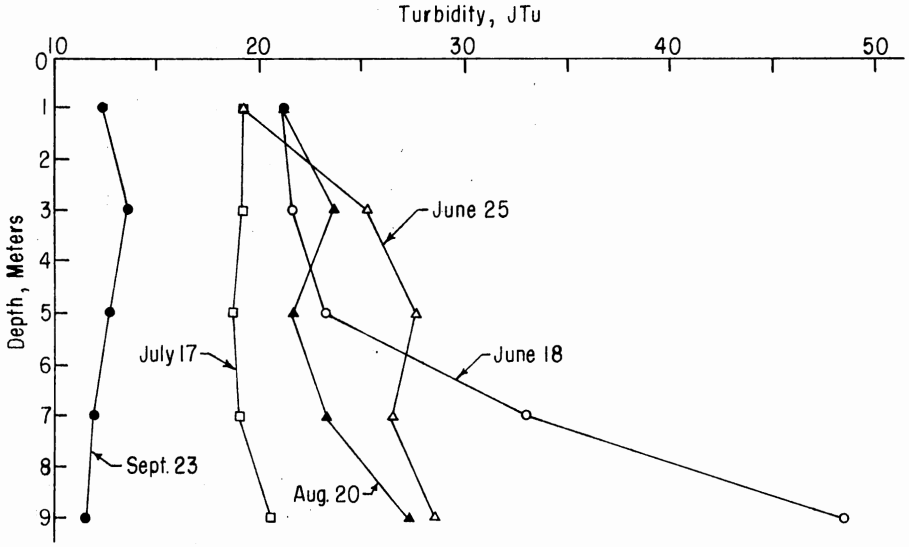

Figure 59. Selected Profiles of Turbidity

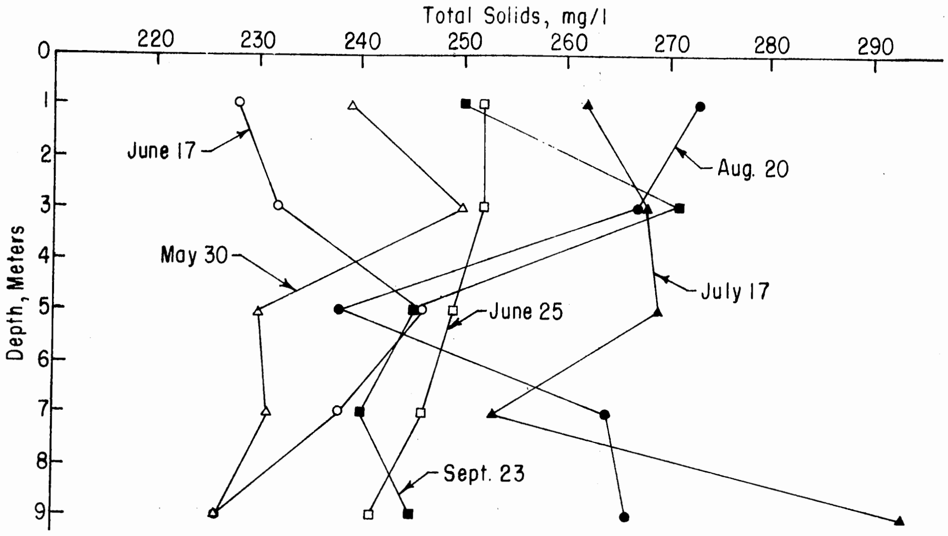

Figure 60. Selected Profiles of Total Solids

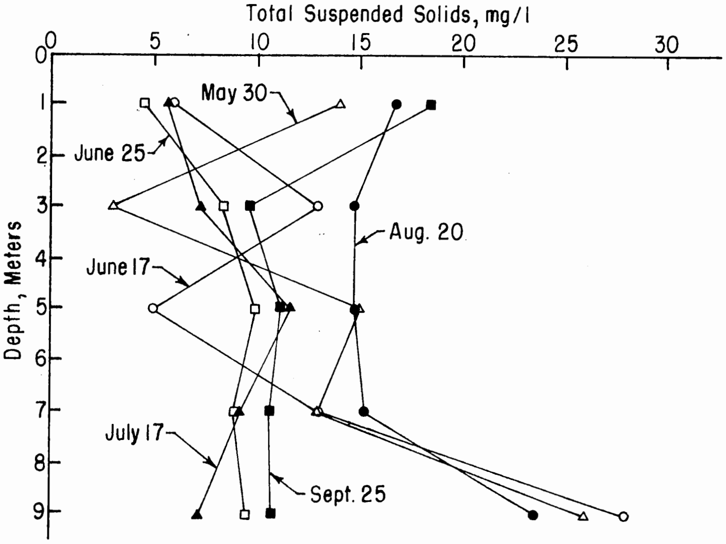

Figure 61. Selected Profiles of Total Suspended Solids

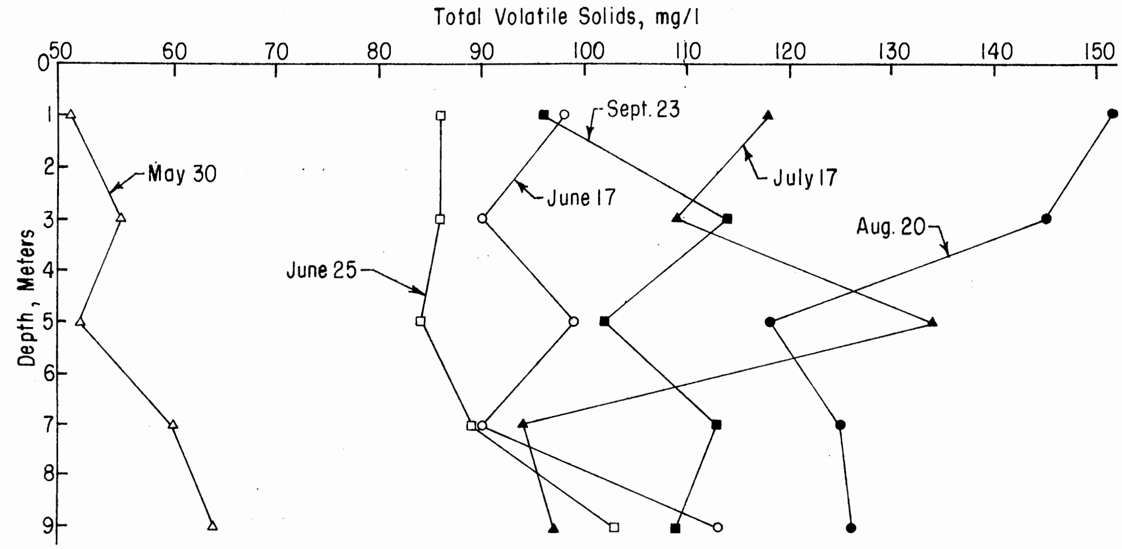

Figure 62. Selected Profiles of Total Volatile Solids

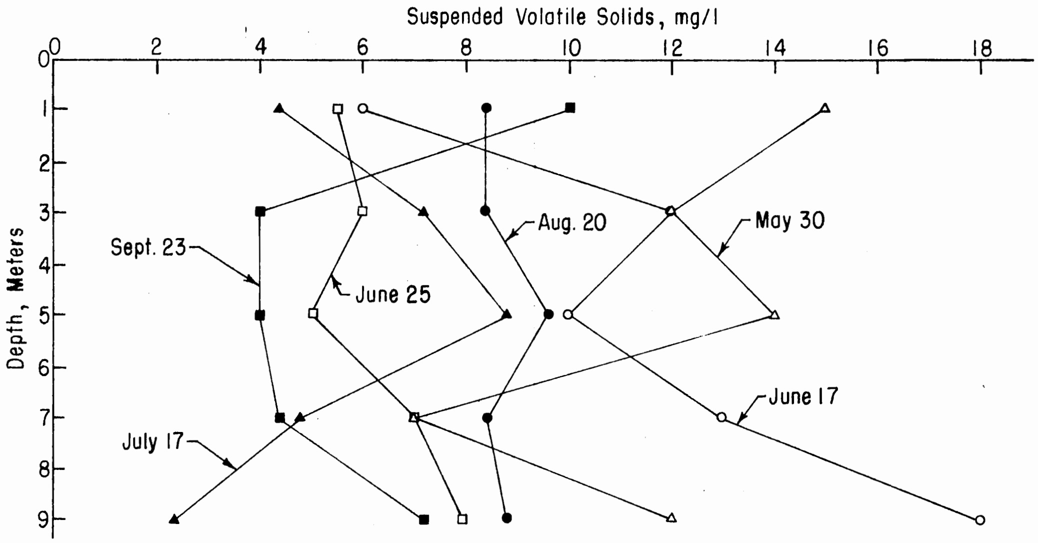

Figure 63. Selected Profiles of Suspended Volatile Solids

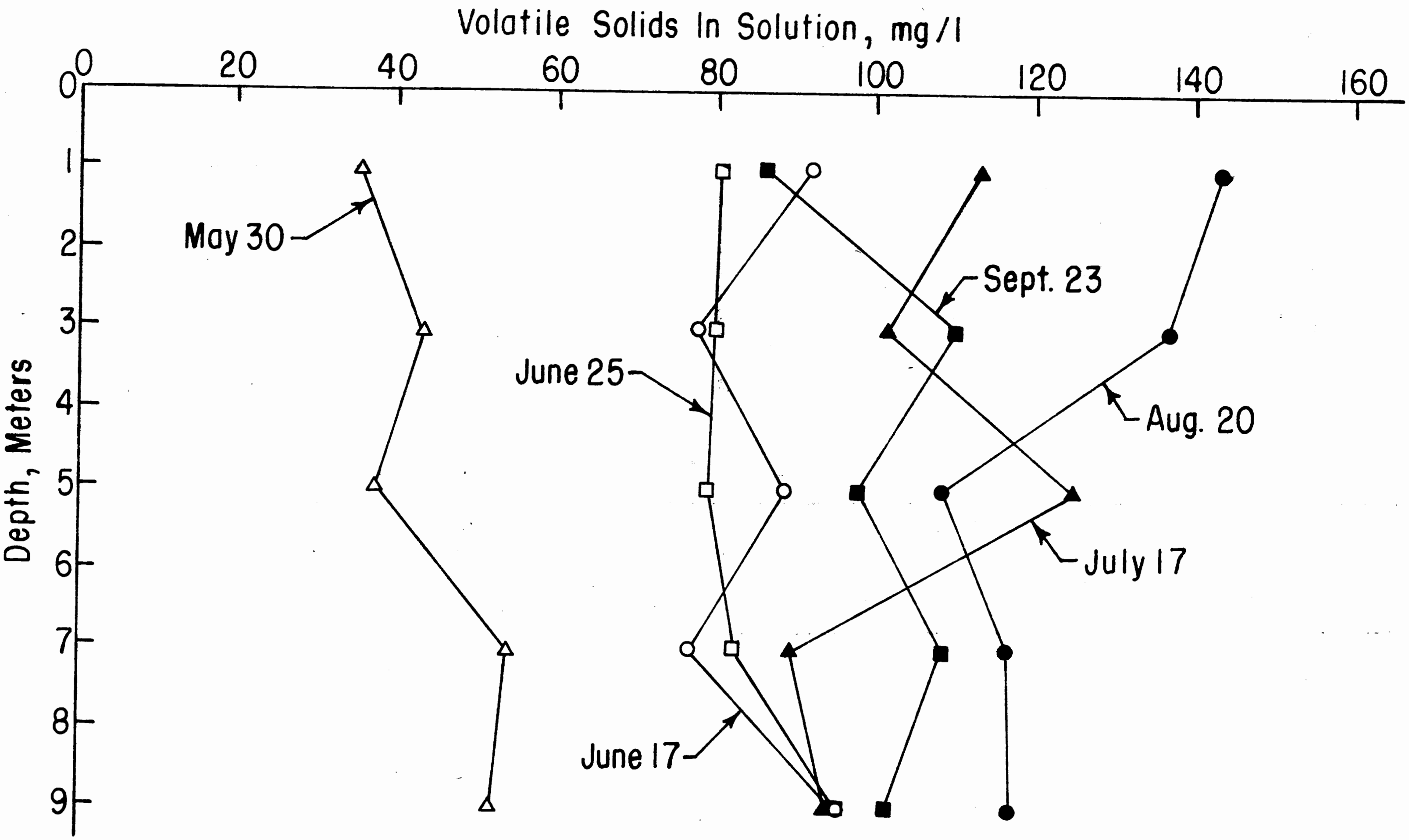

Figure 64. Selected Profiles of Volatile Solids in Solution

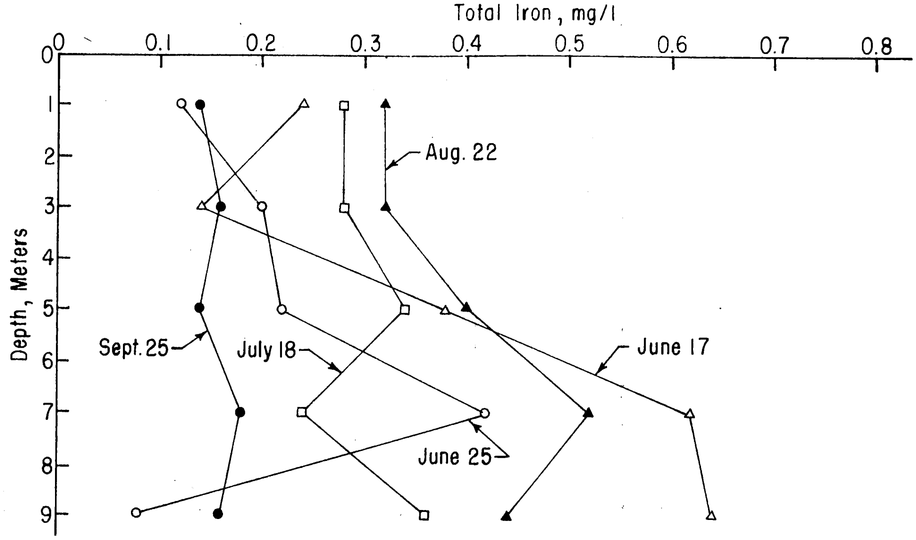

Figure 65. Selected Profiles of Total Iron

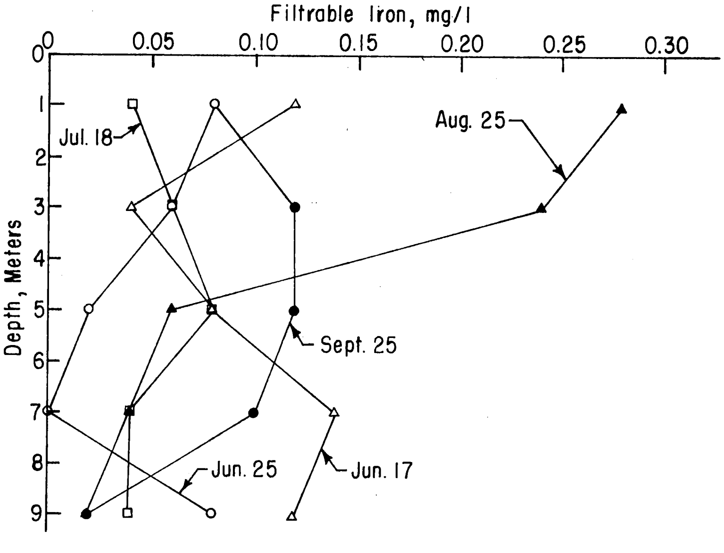

Figure 66. Selected Profiles of Filtrable Iron

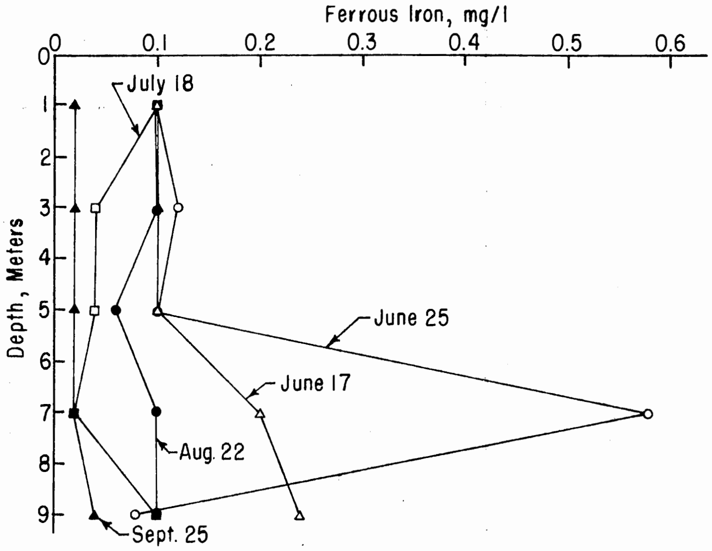

Figure 67. Selected Profiles of Ferrous Iron

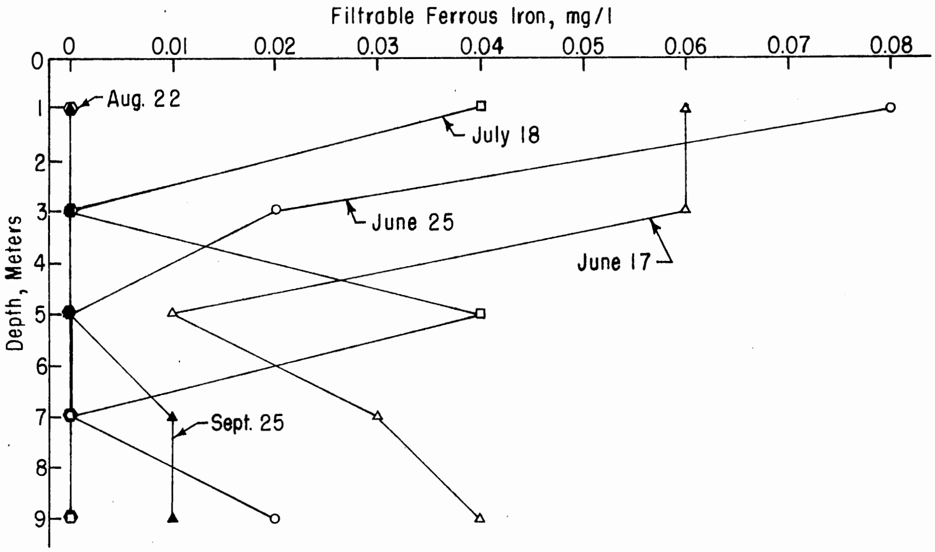

Figure 68. Selected Profiles of Filtrable Ferrous Iron

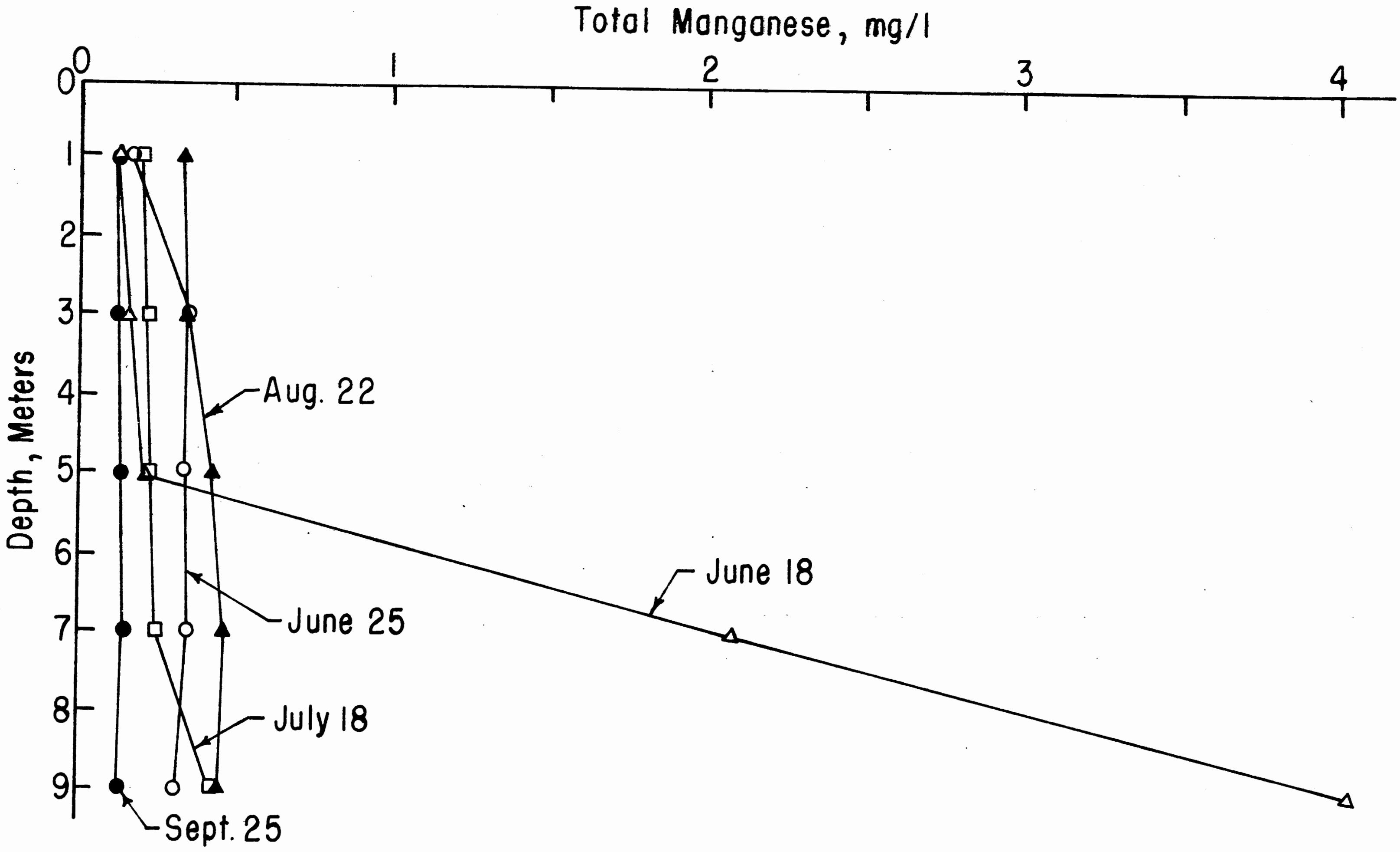

Figure 69. Selected Profiles of Total Manganese

VITA

Randall Gordon Strecker

Candidate for the Degree of

Master of Science

Thesis: DESIGN, CONSTRUCTION, AND EVALUATION OF A PROTOTYPE LOW-ENERGY LAKE DESTRATIFIER

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Biographical:

Personal Data: Born in Fredrick, Oklahoma, October 28, 1951, the son of Calvin G. and Maybelle Strecker.

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Professional Experience: Served as a Graduate Research Assistant from December, 1974, to July, 1976, and a Graduate Teaching Assistant from January, 1976, until May, 1976, for the Agricultural Engineering Department of Oklahoma State University.

Professional and Honorary Organizations: Student member of the American Society of Agricultural Engineers; National Society of Professional Engineers; Oklahoma Society of Professional Engineers, Tau Beta Pi, Registered Engineer-In-Training, State of Oklahoma.